elementenergy

Hybrid Heat Pumps

Final report

for

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Element Energy Limited
Suite 1, Bishop Bateman Court,
Thompson's Lane, Cambridge,
CB5 8AQ
Tel: 01223 852499

Contents

This report was commissioned by the Department for Business, Energy & Industrial Strategy (BEIS) and led by Element Energy with support from Eider Consulting.

Authors

For comments or queries please contact:

Sam Foster sam.foster@element-energy.co.uk

Sophie Lyons sophie.lyons@element-energy.co.uk

Ian Walker ian.walker@element-energy.co.uk

Tel: 0330 119 0990

Eider Consulting

Tim Thurnham

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- Guy Cashmore, Kensa
- Max Halliwell, Mitsubishi Electric
- Adrian McLoughlin, Newcastle City Council
- Phil Hurley, NIBE
- Chris Underwood, Northumbria University
- Ian Rose, PassivSystems
- Edwin Carter, PassivSystems
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- Nick Salini, Thermal Earth
- Christian Engelke, Viessman
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- Mitchell Cogger, Worcester-Bosch

1 Executive summary

Heating and cooling currently accounts for nearly half of UK energy consumption, and around 50% of UK emissions from heating are associated with space heating and hot water in domestic buildings. As such, decarbonisation of domestic space heating and hot water will be vital for the reduction of UK carbon emissions by 80% by 2050 relative to 1990 levels, as required under the Climate Change Act.

Domestic heating in the UK is currently dominated by natural gas. Various low carbon heating technologies could be used to decarbonise the UK's heat supply, alongside the reduction of heat demand through deployment of more energy-efficient technologies. Electric heating options such as heat pumps are amongst the technologies that are likely to be required for decarbonisation. However, electrification of heat has the potential to incur high costs at an energy system level (e.g. by requiring reinforcement of electricity distribution networks). Hybrid solutions which use gas as well as electricity to meet the heat demand could help to address this challenge.

This study was commissioned by BEIS **to advance the understanding of the potential role of hybrid heat pump (HHP)** systems in the UK's long-term decarbonisation of domestic heat. For the purposes of this study, a HHP system is defined as one combining an electrically-driven heat pump with a gas boiler, along with a dedicated controller.

The study draws on a wide range of sources (including a review of existing literature and field trial data, consultation with industry stakeholders, and the results of dedicated technical modelling) to identify key opportunities where HHP systems could offer improvements over gas boilers and / or standalone heat pumps, in terms of the following factors:

- **Carbon emissions intensity** of heating (e.g. gCO_2/kWh);
- **Cost-effectiveness** (in terms of upfront capital cost and lifetime cost of heating i.e. net present cost);
- **Impact on the wider energy system** (in particular the **peak electricity** demand during the coldest days of the year, and demand flexibility);

The main findings of the report can be separated into performance and cost related aspects, and they are summarised under these categories below.

1.1 Performance of HHPs

Performance of HHPs varies across different house types. Most of the results in this study are shown for a 'typical semi-detached house', and as such, the impacts of other parameters are discussed below in terms of their effects on HHP performance for this house type (unless otherwise specified).

1.1.1 Carbon emissions intensity

The **carbon emissions intensity** of heating attributed to a HHP system is influenced by several factors, the most material of these being:

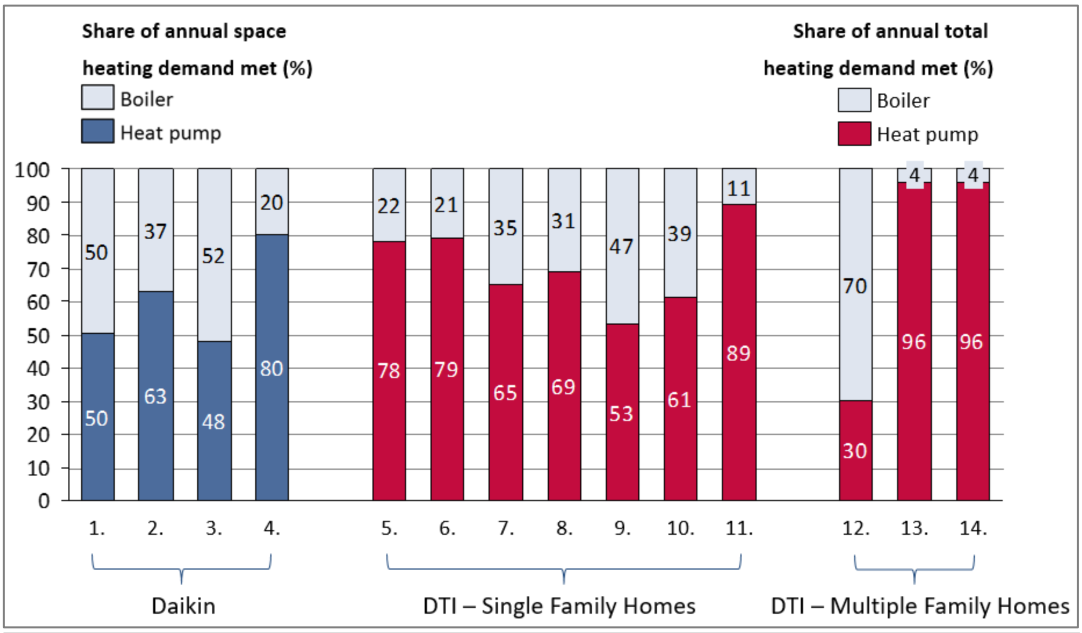
- capacity of the heat pump component, relative to the peak heating demand;
- heating schedule followed (e.g. continuous or twice a day heating);
- hybrid mode (i.e. switch or parallel) if a twice a day heating profile is followed
- mode of domestic hot water (DHW) heating.

Emissions intensity is also affected (to a lesser extent) by the type of emitters and the HHP control strategy.

The **capacity of the heat pump** in relation to the heating demand of a building ultimately determines how much heat can be provided using the heat pump, and how much must be provided by the gas boiler. Alongside the heat pump COP, this is fundamental to determining the potential emissions savings of a HHP. As such, the technical modelling aspect of this study considers a default case where the heat pump component of a hybrid system is sized to comfortably meet the entire space heating demand on an average winter day, when the HHP follows a continuous heating schedule. This ensures that the default case considers the maximum possible emissions savings (subject to the impacts of other operating conditions).

Observed data on the share of heat demand met by the HP component of HHPs suggests that in practice, this is highly variable. Figure 1-1 shows a selection of field trial results on the share of annual heat demand met by different components of a hybrid system, when installed in various house types with different levels of energy demand.

Figure 1-1 Observed share of annual heat demand met by heat pump and boiler components of hybrid systems

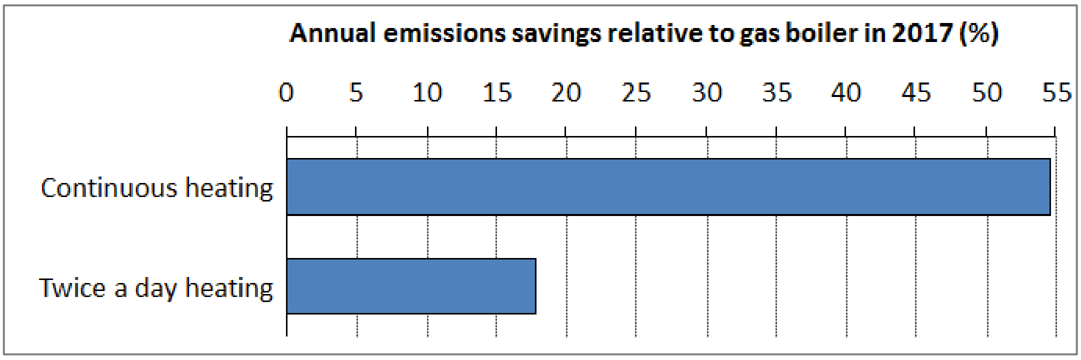


No.	Source	Monitoring period	Total heat production (HP + Gas boiler) [kWh]	House type
1.	Daikin, 2017	July 2014 - March 2015	11,490	Two bedroom terraced house
2.		April 2014 - March 2015	3,452	Three bedroom semi detached bungalow
3.		May 2014 - March 2015	5,889	Three bedroom semi detached house
4.		May 2014 - March 2015	10,610	Three bedroom semi detached house
5.	DTI, 2015	October 2014 – September 2015	17,716	Single family home
6.			10,502	Single family home
7.			12,062	Single family home
8.			15,206	Single family home
9.			15,687	Single family home
10.			15,823	Single family home
11.			22,773	Single family home
12.			78,430	15 apartments, 936 m^2 heated
13.			91,350	18 apartments, 1099 m^2 heated
14.			88,410	19 apartments, 1151 m^2 heated

These results show that the share of heat met by a heat pump component of a hybrid system can be as low as 30%, or as high as 96%, with various values in between. The variation in the results suggests that house type, which impacts the total heat demand of a building, is likely to be a factor influencing the heat pump share of the annual demand and thus the emissions savings.

Heating schedule can also drastically alter the share of demand met by the heat pump component, and could account for some of the variation seen in Figure 1-1. A twice a day heating profile has high peaks in heat demand which require high flow temperatures, and must therefore be met by the boiler instead of the heat pump. This reduces the emissions savings of the HHP relative to a gas boiler. For example, Figure 1-2 shows that the annual emissions savings that could be achieved by a HHP installed in 2017 would be 55% under a continuous heating schedule, but only 18% for a twice a day heating schedule.

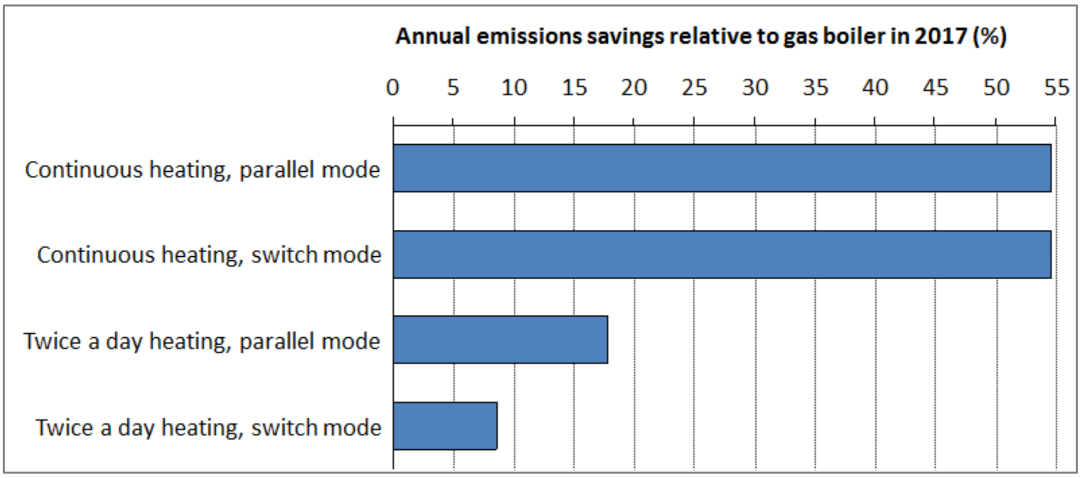
Figure 1-2 Impact of heating schedule on carbon emissions for a HHP in a typical semi-detached house



For some operating conditions, using a **switch hybrid mode** (where the entire heat demand for a certain period is met by the boiler if the HP component cannot meet the demand in that period) rather than a parallel hybrid mode (assumed to be the base case for HHPs, where the HP can contribute some heat during that period) can significantly reduce the emissions savings achieved. This is most likely to be the case for a system operating on a twice a day heating schedule, when the maximum output temperature of the HP can be a limiting factor (an effect which is exacerbated when the house does not have low T emitters installed, which is assumed to be the case for many HHPs).

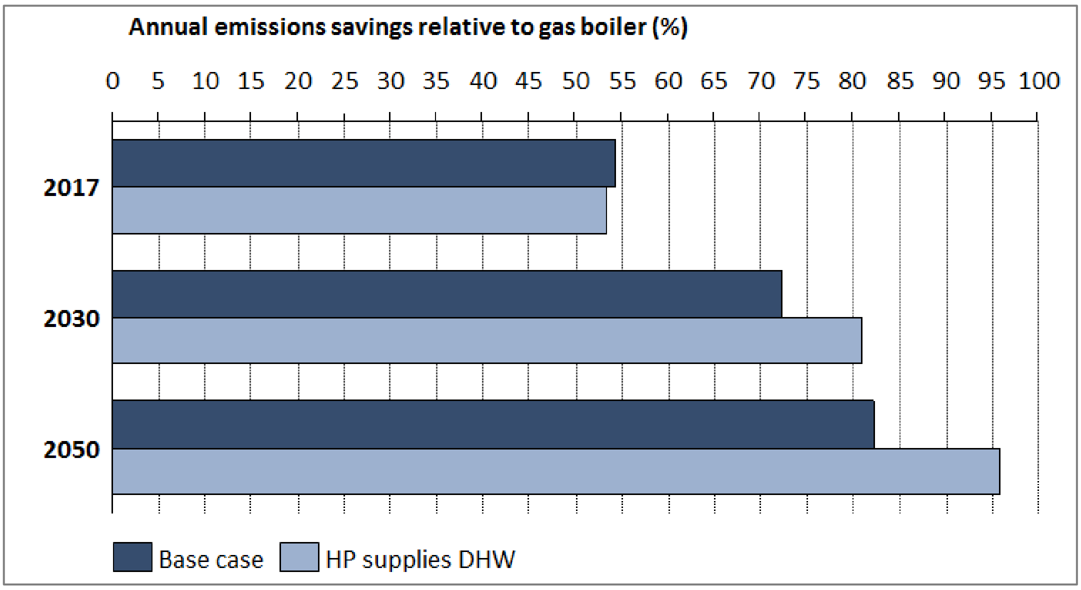
Figure 1-3 shows the impacts of operating in a switch mode on the annual emissions savings in 2017, compared to operating in parallel mode, for a HHP in a typical semi-detached house with high temperature (high T) emitters. In the twice a day heating case, using the switch mode leads to the emissions savings dropping to 9% (compared to 18% in parallel mode). However, using switch mode has no impact on the emissions savings for continuous heating. In this case, the flow temperature requirements for space heating are within the capabilities of the HP, so it can meet the whole demand in each time period, meaning that there is no difference between switch and parallel operation. Note that the boiler is assumed to meet the entire DHW demand in both cases.

Figure 1-3 Impact of hybrid mode on carbon emissions for a HHP in a typical semi-detached house (high T emitters)



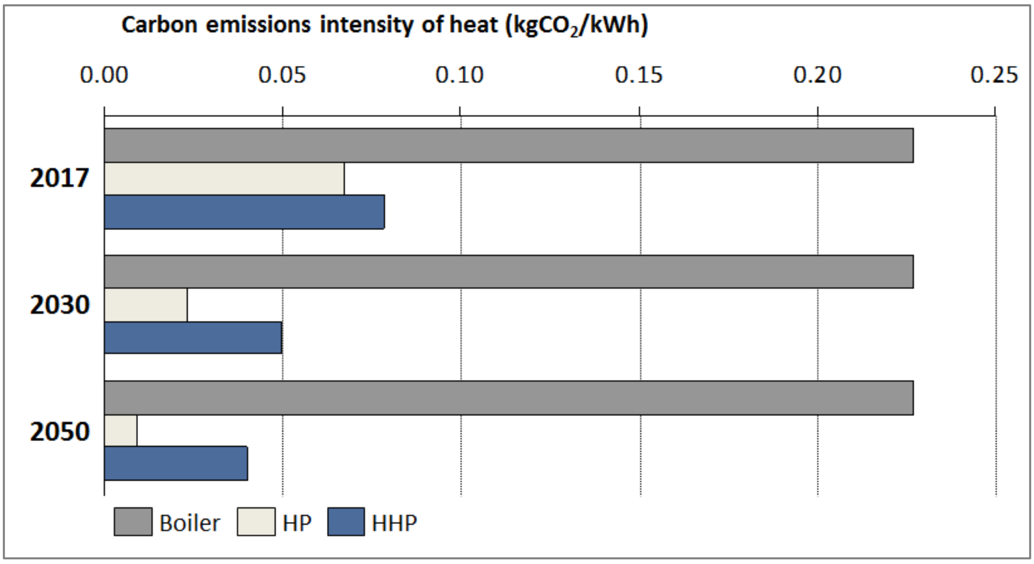
The mode of **domestic hot water heating** also impacts the carbon emissions intensity, due to the effect on the overall share of demand met by the heat pump component. For a HHP with a sufficiently sized heat pump, the share of heat demand met electrically could be maximised by generating DHW throughout the day using the heat pump (instead of the boiler component) and using thermal storage to store the heat until required. Due to the relatively low efficiency of the heat pump at the higher levels of demand for this case (and consequently higher flow temperatures), emissions savings compared to the base case would only be realised once further decarbonisation of the electricity grid has been achieved. The effect of decarbonisation on the two modes is shown in Figure 1-4.

Figure 1-4 Impact of DHW provision on carbon emissions from a HHP in a typical semi-detached house – shown for first year of operation only



For some building types, including the ‘typical semi-detached’ case, HHPs can currently achieve emissions savings (relative to gas boiler heating) which are very similar to those achieved by standalone heat pumps. The projected carbon intensity for the different heating systems, taken over the lifetime of the system, is shown in Figure 1-5.

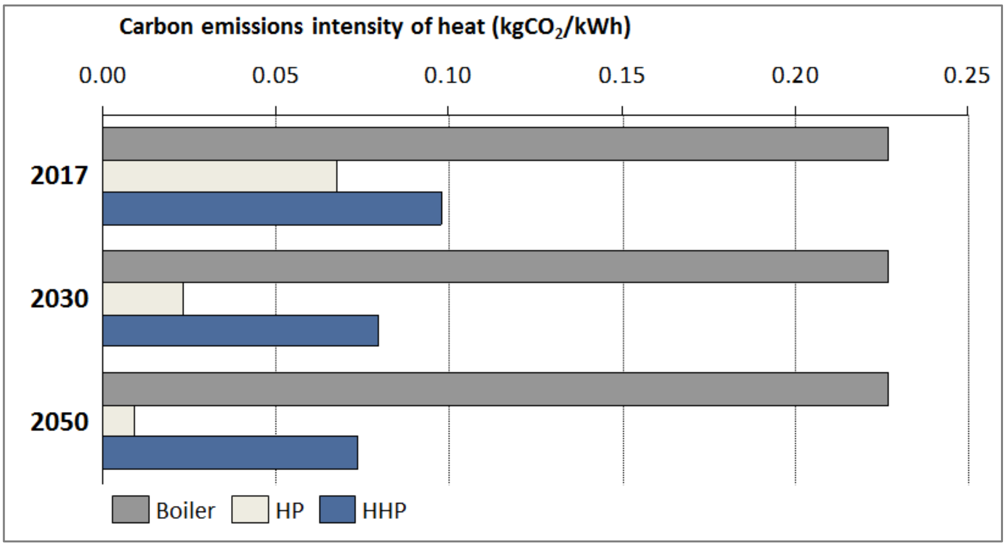
Figure 1-5 Projected carbon intensity of heat for HHP, HP and boiler heating systems (typical semi-detached, DHW met by the boiler component of HHP) – measured over 15 year lifetime



In the default case shown here, the savings compared to the boiler increase over time for the HHP and the HP, reflecting the decarbonisation of the electricity grid. However, this also means that over time, the emissions benefits of the standalone heat pump over that of the HHP also increase.

For very efficient buildings, the emissions savings of HHPs compared to standalone HPs are lower, even for systems installed in 2017. This is largely due to the higher share of the total heat demand coming from DHW (which is assumed to be met by the boiler in the default HHP system). The corresponding projected lifetime emissions values for a 'zero carbon' new build semi-detached are shown in Figure 1-6.

Figure 1-6 Projected carbon intensity of heat for HHP, HP and boiler heating systems (zero-carbon semi-detached with low T emitters, DHW met by the boiler component of HHP) – measured over 15 year lifetime



1.1.2 Peak electricity demand

The following parameters can significantly impact the **peak electricity demand** from a HHP system, as well as affecting the **maximum additional domestic electricity demand during the evening peak period**:

a) capacity of the heat pump component, relative to the heating demand;
b) mode of domestic hot water (DHW) heating;
c) type/sizing of emitters;
d) choice of hybrid mode (switch or parallel);
e) HHP control strategy.

The **capacity of the heat pump** in relation to the heating demand of a building determines how much heat can be provided electrically, and thus can provide an upper limit on the electricity demand from a hybrid system.

The effect of the mode of **domestic hot water heating** on the peak demand met by the heat pump component directly impacts the peak electricity demand; if the heat pump is used to provide DHW this can increase the peak electricity demand, compared to the case where the DHW is always provided by the boiler.

Using **low temperature (i.e. larger) emitters** can also reduce the peak electricity demand, compared to the default case where standard or 'high temperature' emitters are used. Heat pumps operate more efficiently at lower temperatures, and therefore for a given heat demand, the electricity demand from the heat pump component will be lower.

Using **switch hybrid mode** rather than a parallel hybrid mode may result in a lower peak electricity demand for the twice a day heating schedule; in this case, if the HP component cannot meet the whole peak demand, the boiler meets the entire demand at this time.

Figure 1-7 and Figure 1-8 show the impacts of the parameters described above on the peak electricity demand of a HHP in a typical year, and on the maximum additional electricity demand from HHPs observed in the evening peak period. Values are also shown for the equivalent cases for a standalone HP.

Figure 1-7 Peak electricity demand for HHP and HP systems in typical semi-detached (assumes electric resistive backup in the standalone HP case)

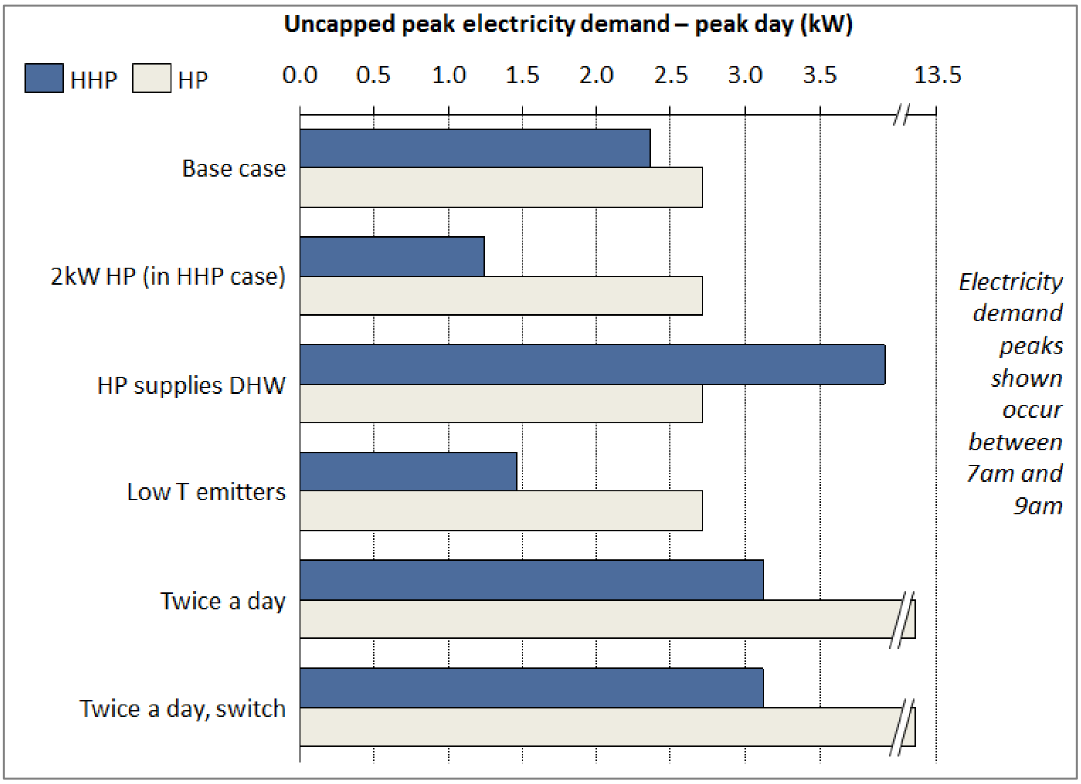
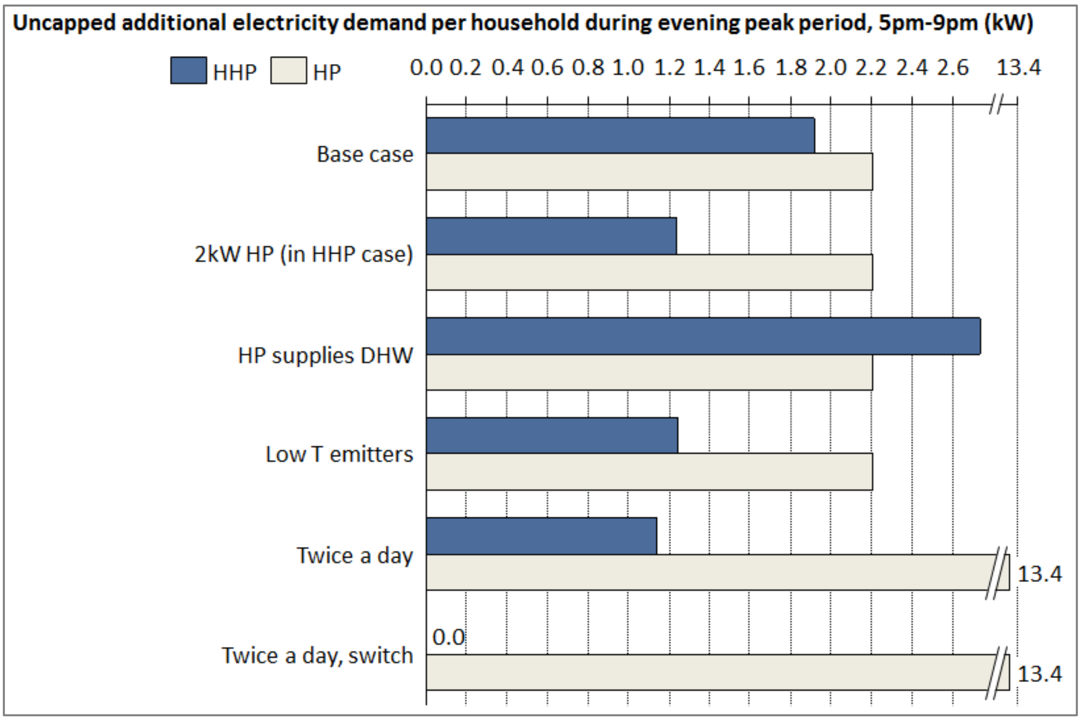


Figure 1-8 Additional electricity demand during evening peak period, for HHP and HP systems in typical semi-detached (assumes electric resistive backup in the standalone HP case)



As well as showing how the peak electricity demand is affected by the different parameters, the values in Figure 1-7 and Figure 1-8 illustrate the general finding that

HHPs have the potential to significantly reduce the peak electricity demand compared to a standalone HP, assuming that electric resistive heating is used as a backup in the standalone HP case. The only case for which this is not necessarily true is the case where the DHW demand is met by the heat pump component of a HHP system. In this case, at the time of peak demand, the heat pump provides space heating as well as filling the DHW store[1]. The efficiency of the heat pump will be lower in the HHP case due to the use of High T emitters, compared to Low T emitters in the standalone HP case. This leads to a higher peak in electricity demand in meeting the same level of heat demand.

Alongside the options for peak reduction shown in Figure 1-7 and Figure 1-8, various control strategies could be used within a hybrid system to fundamentally limit the conditions at which the heat pump works, thereby reducing the peak electricity demand. This could be as simple as adjusting the temperature set-point so that at times of peak demand (i.e. on colder days) the boiler takes over. More advanced ‘smart’ controllers could potentially enable the heat pump to switch off (or turn down, in a parallel hybrid mode) in response to grid signals at times of peak network loading, or in response to dynamic pricing. These strategies may reduce the overall emissions benefits of HHPs, even when the higher emissions of electricity generated during the evening peak period is taken into account, but nevertheless this capability is one of the main motivations for considering HHPs as an alternative to standalone heat pumps.

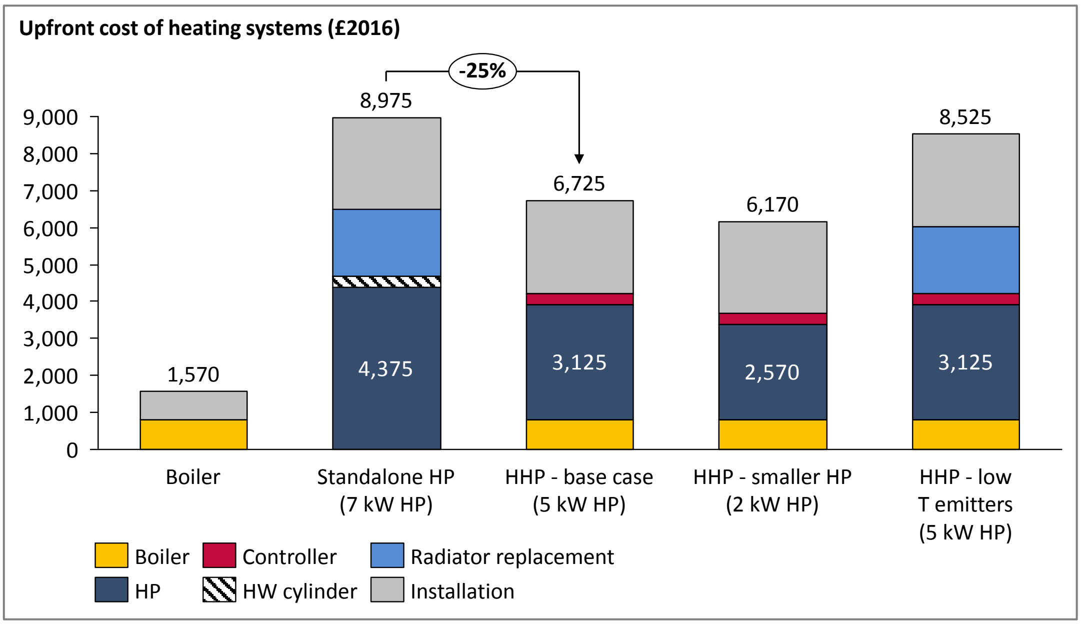
1.2 Cost of HHPs

1.2.1 Upfront costs

As with the performance aspects, the cost of a HHP varies according to various system parameters. Figure 8-10 shows the breakdown of costs for a packaged HHP system in a few different configurations, compared to a standalone heat pump and a gas boiler, for a typical semi-detached house. Values shown are mean results from the range found in the literature and through the industry consultation.

[1]While this assumes that the store is filled at times of lowest demand, for a continuous heating profile, DHW generation inevitably coincides with space heating.

Figure 1-9 Upfront costs of HHP, HP and boiler heating systems for a typical semi-detached (central cost case)

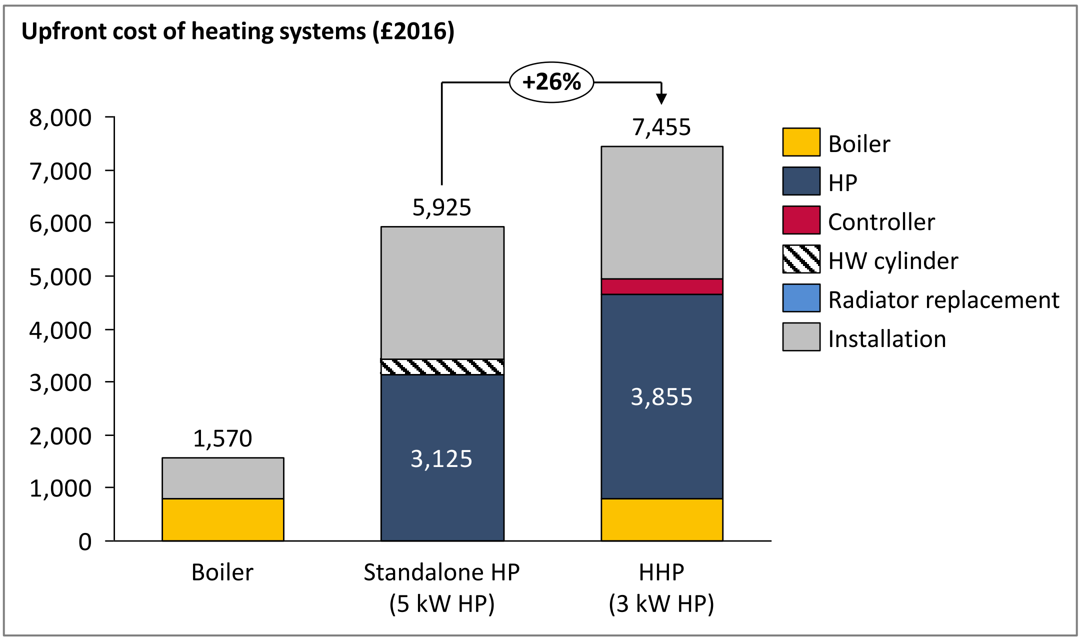


As shown in Figure 1-9, for a typical semi-detached house, HHPs and standalone HPs carry a cost premium of around £5,000-£7,500 over the gas boiler case. However, **HHPs currently offer upfront cost savings of £450-£2,800 compared to a standalone HP, for a typical semi-detached house**. Savings mainly result from the ability not to replace existing emitters (radiators) with low-temperature emitters in the HHP case, and also the ability to reduce the rated capacity of the heat pump component in the HHP case compared to the standalone HP case. Additional savings can be realised by choosing to provide DHW with a combi boiler, thus avoiding the cost of a hot water cylinder required for DHW generation by the heat pump.

It should be noted that in the case shown in Figure 1-9, the cost differential between the HP components of the HHP in the base case and the 'smaller HP' case is only £555, for a 2kW system versus a 5kW system. This is because cost per kW value used for heat pumps below 5kW capacity was significantly higher than the equivalent cost for heat pumps above 5kW. Although the two values are based on the available literature and industry consultation, there was only one data point for the smaller heat pumps. It is possible that in future, perhaps as a greater number of sub-5kW heat pumps enter the market, the cost of those smaller HPs could reduce further.

For highly efficient new builds, however, HHPs may not bring upfront cost savings over standalone HPs. For example, Figure 1-10 compares the capital costs for the different heating systems in a new build, 'zero carbon standard' semi-detached house.

Figure 1-10 Upfront costs of HHP, HP and boiler heating systems for a zero carbon (new build) semi-detached (central cost case)



Due to the lower space heating demand of the zero carbon (new build) house type versus the typical semi-detached house type, it is assumed that the heat pump components in the HHP case and the HP case are smaller in size compared to those used in the typical semi-detached house (3kW and 5kW in the zero carbon semi-detached house respectively, compared to 5kW and 7kW in the typical semi-detached house). Due to the higher price per kW of smaller systems assumed here based on the available data (see discussion above), this means that the heat pump cost is higher for the HHP than the standalone HP case (see Section 1.5 for a description of the caveat to this analysis). More significantly, it is assumed that this house type (new build) is fitted with low T emitters at the point of construction, meaning that the HHP case does not benefit from avoiding the costs of low T emitters. Taking into account the additional cost of the boiler and controller unit for the HHP, this makes the HHP case 26% more expensive than the HP case. This result should be treated with some caution, as the heat pump component costs are highly sensitive to the £/kW assumptions for systems below 5kW (for which data was very scarce). However, the avoided cost of emitter replacement in the HP case for highly thermally efficient buildings is the more important driver, and irrespective of the comparative HP cost, this will reduce the economic benefit of HHPs relative to HPs in those building types.

The literature review and stakeholder consultation revealed considerable uncertainty around future costs of HPs and HHPs, but broad agreement that there is scope for some level of cost reduction, both in product costs (mainly for the heat pump component) and notably in the installation costs. Three cost reduction scenarios were developed based on the information available, to capture the range of potential costs for HHPs going forward to 2050. These scenarios are shown for product costs and installation costs in Table 1-1 Table 8-1 and Table 1-2 respectively.

Table 1-1 Summary of product cost reduction scenarios

Scenario	Product cost reduction compared with 2017 (%)			Description
	2030	2040	2050	
High	30%	30%	30%	Annual sales increase to the 100,000s, and this level sustained through the 2020s, leading to a 30% cost reduction by 2030
Central	17%	30%	30%	Annual sales increase to the 100,000s only by the late 2020s, leading to a 30% cost reduction by 2040
Low	0%	0%	0%	Little to no increase in annual sales versus 2017; alternatively, sales increase but improvements in product efficiency mean prices do not reduce significantly

Table 1-2 Summary of installation cost reduction scenarios

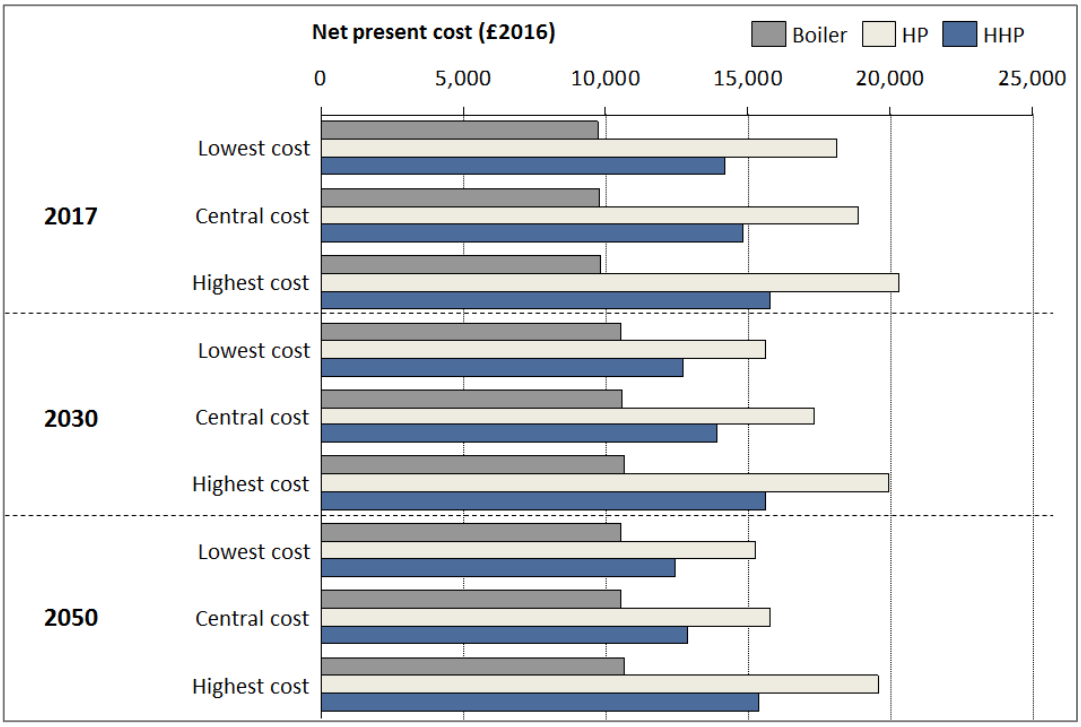
Scenario	Installation cost reduction compared with 2017 (%)			Description
	2030	2040	2050	
High	30%	30%	30%	Annual sales increase to the 100,000s, and this level sustained through the 2020s, leading to a 30% cost reduction by 2030
Central	17%	30%	30%	Annual sales increase to the 100,000s only by the late 2020s, leading to a 30% cost reduction by 2040
Low	10%	10%	10%	Little to no increase in annual sales versus 2017; small increase in competition leads to 10% cost reduction by 2030

1.3 Net present cost

Due to the significant upfront cost premium of HHPs and HPs versus the gas boiler counterfactual, the lifetime costs of those options substantially exceed those of the gas boiler option. However, HHPs can, for some building types, offer large lifetime cost savings over HPs.

For example, Figure 1-11 shows a comparison of the net present cost (NPC) of the HHP, standard HP and Gas boiler options, for installations in different years, for the central cost scenario (central values for current costs, and the central cost reduction case). For the typical semi-detached building, in 2017, the NPC of the gas boiler counterfactual is approximately £11,000. The NPC of the HHP is around £15,000 in the central case, which is significantly higher than the boiler case, but offers savings compared to the HP case, which is £19,000.

Figure 1-11 Net present cost comparison: base case for typical semi-detached. Assumes a 15 year lifetime and a 3.5% discount rate.



The lifetime savings of the HHP option versus the HP option for the typical semi-detached case are due both to the **upfront cost savings**, as discussed in the previous section, which are **in the region of £2,000** for the case considered here, and to a lower ongoing fuel cost.

The lower fuel cost for HHPs versus HPs is mainly due to the use of the gas boiler to provide the DHW demand in the HHP case, combined with the price premium of electrical heating versus gas heating. The electricity to gas price ratio over the period 2017 to 2050 ranges between approximately 4 and 5; since the typical SPF achieved by the HP is less than 3 in the winter months, gas heating remains lower in cost than electrical heating using the HP over the whole time period 2017-2050 and in all scenarios considered[2]. Since the DHW demand is met by the Gas boiler in the HHP case, and this corresponds to 15% of the total heating demand, this leads to substantial ongoing cost savings of more than £100 per year, resulting in **further lifetime cost savings in the region of £2,000** (discounted at 3.5%) compared to the HP case.

It should be noted that these cost savings do not include any valuation of the reduced peak electricity demand achieved by the HHP compared to the HP. This could bring further reductions on a lifetime cost basis relating, for example, to time-of-use tariffs (where the higher tariffs could be avoided by switching to the gas boiler) or peak period rebates. This is likely to be relevant in the medium term, when the value of peak electricity reduction could become significant.

For highly efficient buildings, HHPs are less likely to offer lifetime cost savings relative to HPs, due to the relatively low heat demand to be met, the reduced cost differential for the heat pump components of the two systems, and the additional cost of the boiler and the controller in the HHP case (shown in Figure 1-10).

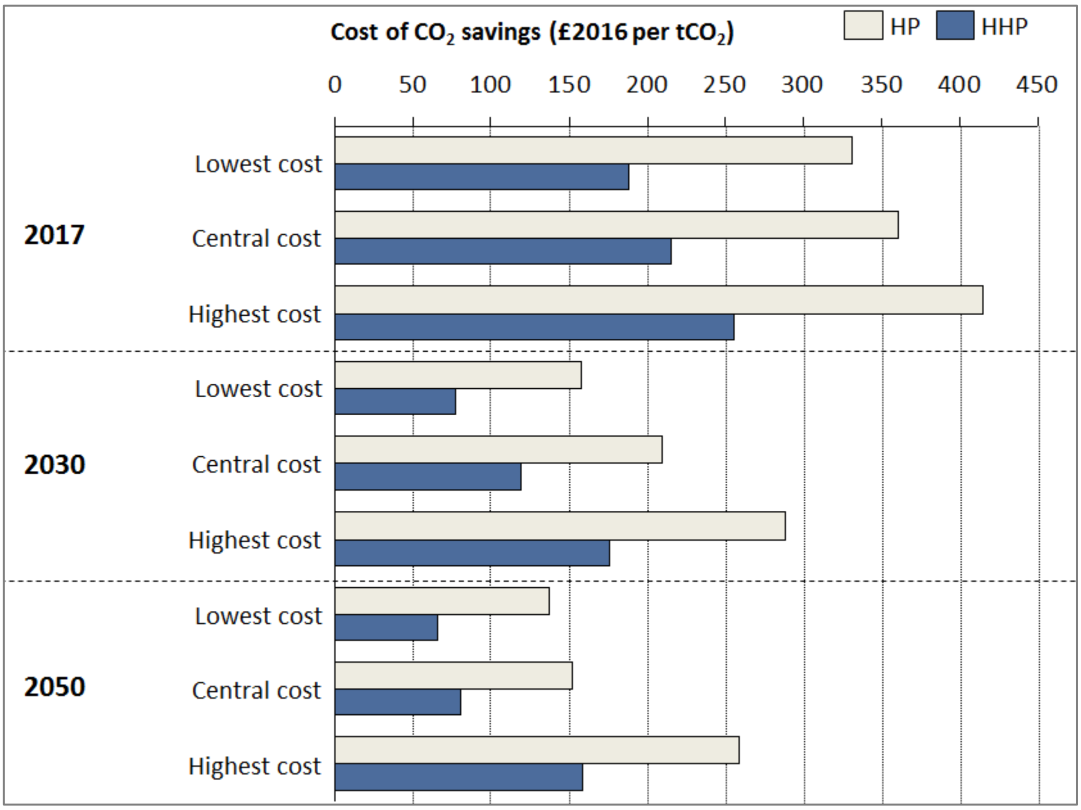
[2] Note that inclusion of carbon prices (not included here) could significantly alter the results particularly for installation in 2050.

1.4 Cost of emissions savings

This study derived scenarios for the **cost of carbon emissions savings** of the HHP and HP options versus the Gas boiler case by combining the evidence on lifetime net present cost with the evidence on the carbon intensity of heating.

Overall, the analysis suggests that for **typical existing buildings, HHPs offer substantially more cost-effective heat decarbonisation option than standard HPs**. This is shown in Figure 1-12, which presents the scenarios for the cost of CO_2 savings of HHPs and HPs relative to a gas boiler, for a typical semi-detached building.

Figure 1-12 Cost of CO_2 savings versus Gas boiler: Base case (Typical semi-detached, HHP uses existing emitters and DHW is met by boiler)

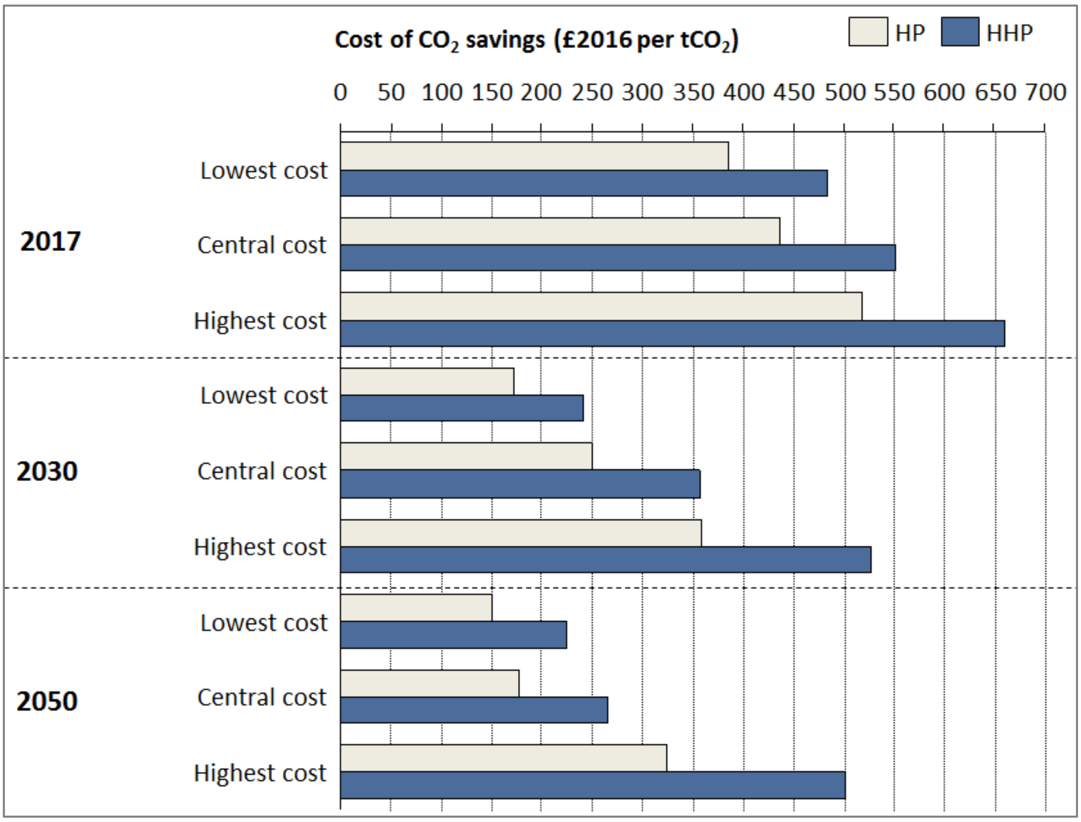


While the cost of CO_2 savings by HHPs remains high in 2017, at more than £100/tCO_2, the cost could fall to below £50/tCO_2 in the optimistic cost reduction scenario by 2030. Under the same cost reduction assumptions, the cost of CO_2 savings from the standard HP at the same point in time are expected to remain above £100/tCO_2.

In this case, the case for HHPs rather than HPs as the most appropriate option for heat decarbonisation rests on whether or not the level of carbon emissions reduction is sufficient. In the near term, the reduction in carbon emissions brought about by a switch from gas boiler to HHP is almost as large as for a switch to a standard HP (see Figure 8-5), and the substantially greater cost-effectiveness provides a strong argument for the use of HHPs. In the longer term, however, it should be recognised that HHPs may not provide the extreme level of decarbonisation desired (unless the carbon content of gas is significantly reduced over time).

In terms of cost-effectiveness, **the opposite trend is observed for highly thermally efficient buildings**, where cost savings can be achieved in the standard HP case since a smaller HP would be sufficient and the cost of replacement of emitters can be foregone. In this case, the HHP offers a less cost-effective alternative, due to the additional cost of the boiler and controller. This is shown in Figure 1-13.

Figure 1-13 Cost of CO_2 savings versus Gas boiler: Zero-carbon semi-detached with low T emitters



In this case, however, the cost of CO_2 savings remains high for both HHPs and HPs, since the greater thermal efficiency reduces the lifetime carbon savings; the cost of CO_2 savings remains above £100/tCO_2 even in 2050 in the most optimistic cost reduction scenario for the standard HP option.

1.5 Limitations of the analysis

Several key limitations of the analysis have been identified, and should be considered when interpreting the findings of this work. These limitations are described below.

Impact of diversity of demand and scaling outputs across the national stock

In order to understand the operation of a hybrid system, it is necessary to study the system at the level of a single building, using an undiversified heat demand profile rather than a diversified demand profile reflecting an average over a large number of households.

If a diversified profile were used in the modelling, this would tend to underestimate the peak heat demand as 'observed' by each individual heating system. As such, the approach would be strongly liable to overestimate the share of heat demand that could be met by the HP component, and to underestimate the peak electricity demand associated with each individual HP. This study focuses on an assessment of HHPs (and standalone HPs) at an individual household level, to ensure that the impact of diversity of demand across multiple households does not lead to an underestimate of those key outputs.

However, this has important implications for the application of these results to the national building stock. While many of the outputs generated, such as the share of heating provided by the HP component and the carbon emissions savings (that is, the outputs which are concerned with monthly or annual averages) can be scaled up additively across the stock, this is not the case for outputs relating to peak electricity demand.

In order to derive the total peak electricity demand associated with HPs across the stock – for example to determine the additional peak electricity demand in the UK or any local region due to HP or HHP deployment – it would be necessary to apply diversity to the individual building peak demand values presented here. This is outside the scope of this study, but we point the reader here to a source of data on diversity for HPs which was used as part of the derivation of the twice a day heating profile (as described in Appendix 9.2). A recent paper by Love et al.[3] presents an analysis of the Renewable Heat Premium Payment (RHPP) field trial data, and uses it to derive an estimate of the impact of uptake of HPs in 20% of the housing stock on the GB national grid evening peak. The data presented in that paper suggests that (with caveats as described in the source) the average peak electricity demand of each individual HP across the full trial period is approximately 4.0 kW. In comparison, the peak electricity demand per HP derived after aggregating all demand profiles – defined as the "after diversity maximum demand" (ADMD) – is found to be approximately 1.7 kW. This suggests a reduction by a factor of around 2.4 between the individual HP peak demand and the aggregate peak demand per HP across a large number of HPs.

Finally, it is noted that to determine the overall increase in peak electricity demand due to greater deployment of HPs, it would be necessary to consider the extent of overlap of the 'new' peak with the 'existing' peak associated with all other electricity demand (that is, the typically observed winter evening peak).

Twice a day heating profile

As described above and in the main body of the report, the modelling comparing HHPs with standalone HP considers two cases for heating behaviour: 'continuous' heating and 'twice a day' heating. The consideration of these two cases reflects the fact that while heat pumps are most efficiently used in a continuous heating pattern, and the associated

[3] Love J. et al (2017). *The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial.* Applied Energy Volume 204, 332-342.

heating systems are designed to be used in this way, user behaviour does not always follow this pattern.

For this reason, the twice a day heating case was studied to illustrate a plausible “worst case” scenario for both standalone HPs and HHPs. In the standalone HP case, the twice a day heating scenario leads to a large peak electricity demand, as it is assumed that electric resistive heating would be used to meet the heat demand beyond the maximum output of the HP in this case. In the HHP case, the twice a day heating scenario leads mainly to greater use of the gas boiler and hence lower carbon emissions savings.

The development of a twice a day heating scenario presented challenges due to the difficulty of developing a representative undiversified HP heating profile for this heating pattern. As described above, it is important to model the system operation using undiversified profiles at the single building level in order to accurately represent the peak demand seen by each HP, and therefore not to overestimate the share of heat demand that could be met by the HP component, as would be the likely outcome using a diversified profile. The methodology used to develop the twice a day profile is described in Appendix 9.2. In summary, the objective in the definition of this profile is to accurately reflect the undiversified peak heat demand observed in a single building, using evidence from the recent paper by Love et al.[4] referred to above.

It is therefore important to emphasise the following caveats to the application of the results generated using the twice a day profile. The profile generated is highly stylised, and defined to represent the undiversified peak heat demand as accurately as possible. However, it is not intended to be representative of the overall profile shape associated with buildings practising twice a day heating. Furthermore, it should be reiterated that this is intended to represent a plausible “worst case”, and the continuous heating profile should be considered the more appropriate case. In particular, it would be expected that in the standalone HP case the heating pattern would tend towards the continuous heating pattern since frequent use of the electric resistive heating backup (as implied in many scenarios employing twice a day heating) would lead to high running costs, leading to corrective behaviour by the building occupant. In the HHP case, however, it may be expected that the twice a day heating pattern could be observed more frequently, given that the boiler would be able to meet the peak demand required without leading to high running costs, and due to the familiarity of users with this type of heating system operation using gas boilers. Indeed, this is identified as a key risk of the HHP option for heat decarbonisation.

Sample size for small heat pumps

An extensive stakeholder consultation and literature review exercise was undertaken to gather cost data for HPs and HHPs across the range of sizes relevant for domestic heating. The data collected is described in more detail in Section 4. A key constraint identified in the data gathering exercise is a dearth of cost data relating to HPs at the smallest end of the size range considered.

Specifically, only one data point was identified relating to a HP less than 5 kW in thermal output. This reflects the small current market for HPs in this size range. However, as described above, small HP units less than 5 kW in output are of high interest in the context of HHPs. In the hybrid case the HP component can be ‘undersized’ relative to the standalone HP case, since peak heat demand can be met by the boiler component. This

[4] Love J. et al (2017). *The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial.* Applied Energy Volume 204, 332-342.

should, in principle, lead to a cost saving relating to the HP component in the HHP case relative to the standalone HP case. However, the single data point for HP units below 5 kW is associated with a relatively high cost in £/kW terms. As presented in Section 4, the HP costs calculated using the median values among the data gathered therefore show a discontinuity below 5 kW. This means that while the cost derived for a 5 kW unit is lower than that for a 7 kW unit, as expected, the resulting cost for a 3 kW unit is higher than for a 5 kW unit.

This impacts mainly on the results derived for the “zero carbon standard” new build semi-detached house type, where HP unit sizes of 5 kW and 3 kW are applied for the standalone HP and the HHP respectively. This does not impact on the base case for the “Typical” semi-detached house type, where HP unit sizes of 7 kW and 5 kW are applied for the standalone HP and the HHP respectively.

It may be expected that if a larger number of HP products enter the <5 kW size range, the cost of those products would reduce. This would favour HHPs relative to standalone HPs in cost terms, reinforcing the upfront cost saving in the typical semi-detached house type (which also includes the avoided cost of emitter replacement), and potentially impacting the outcome of the economic comparison in the zero carbon standard house type.

Nonetheless, we do not consider that this alters the overall conclusion that the benefit of HHPs relative to standalone HPs (in terms of both consumer economic case and peak impact on the electricity grid) is substantially stronger in existing and less thermally-efficient buildings than in new buildings.

2 Introduction

2.1 Context and objectives

Heating and cooling currently accounts for nearly half of UK energy consumption and one-third of the UK's greenhouse gas emissions[5]. Around 50% of emissions from heating are associated with space heating and hot water in the UK's domestic buildings. It is therefore clear that decarbonisation of domestic space heating and hot water will be an important component of the UK's strategy to reduce carbon emissions by 80% by 2050 relative to 1990 levels, as required under the Climate Change Act.

Domestic heating in the UK is currently dominated by natural gas, with minority contributions from electricity, solid fuel and oil heating. A range of potential options are available to decarbonise the UK's heat supply, including increased electrification through use of heat pumps or resistive heating; the rollout of heat networks incorporating sources of waste and secondary heat; the use of biomethane or solid biomass in place of natural gas; the use of hydrogen in place of natural gas – as well as the reduction of heat demand through deployment of more energy-efficient technologies. It is likely that a combination of these strategies will be deployed.

This study was commissioned by BEIS **to advance the understanding of the potential role of hybrid heat pump (HHP)** systems in the UK's long-term decarbonisation of domestic heat. For the purposes of this study, a HHP system is defined as one combining an electrically-driven heat pump with a gas boiler, along with a dedicated controller.

This study sets out to build a robust evidence base on the following themes:

- Current in-situ **performance** of domestic HHP systems
- Current **cost** of domestic HHP systems
- Potential for **innovation** to drive performance improvements, cost reductions and consumer acceptance of domestic HHP systems

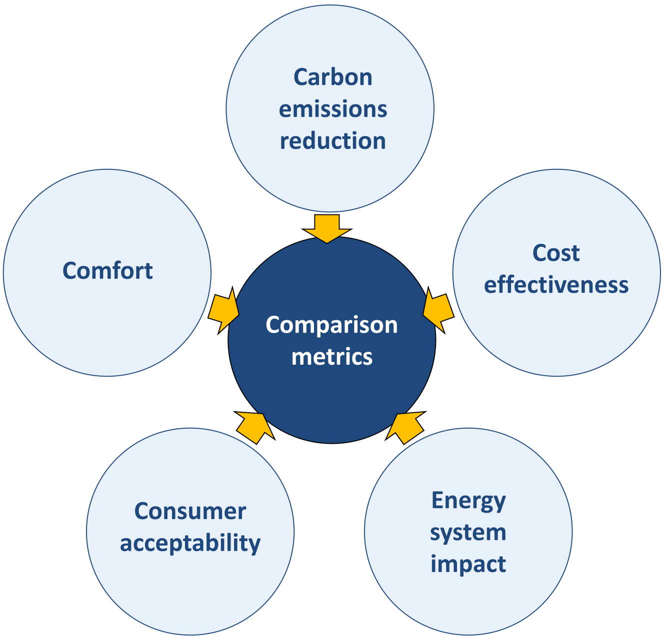
The key point of interest is **how a domestic HHP compares** to a **standard gas boiler** and a **standard (i.e. electric-only) heat pump (HP)** system. In this study, HHPs are compared to air-source HPs rather than ground-source HPs, as they are more likely to be used in equivalent applications; ground-source HP applications are likely to be more restricted due to the requirement for ground loop installation and higher capital costs.

The key comparison metrics are those that represent the requirements for a suitable domestic heating option in the long-term, include:

- Ability to supply sufficient heat to **maintain comfort** year-round
- **Carbon emissions intensity** of heating (e.g. gCO_2/kWh)
- **Cost-effectiveness** (in terms of upfront capital cost and lifetime cost of heating i.e. net present cost)
- **Impact on the wider energy system** (in particular the **peak electricity** demand during the coldest days of the year, and demand flexibility)
- **Consumer acceptability** in terms of space requirements, noise, and other factors

[5] DECC, *Emissions from Heat: Statistical Summary* (2012)

Figure 2-1 Comparison metrics for HHPs with standard HPs and gas boilers

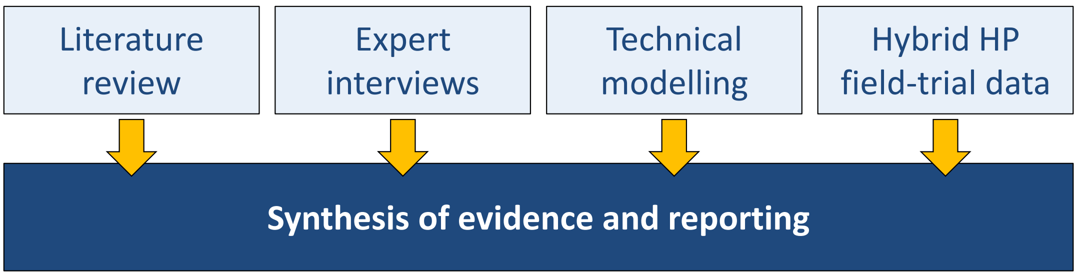


2.2 Summary of approach taken

The approach taken to develop this evidence base, as illustrated in Figure 2-2, is to synthesise information gathered through four complementary workstreams:

- Literature review
- Bilateral interviews with expert stakeholders
- Technical modelling by the project team
- Analysis of HHP field trial data

Figure 2-2 Four complementary workstreams informing the evidence base



Literature review

A range of data sources were included in the literature review, from peer-reviewed academic literature studies to 'grey' literature, including manufacturers' product documentation. Relevant sources were identified using a systematic search strategy based on the research questions described above, and included both sources relating to HHPs specifically, as well as to standard HPs generally, since many aspects of HP cost and performance are of high relevance to HHPs. The findings of the literature review are discussed in an overview of factors influencing cost and performance of HHPs in Section

3. Specific findings from the literature are also described in Section 4, in relation to HHP cost and in Section 5, in relation to HHP performance.

Bilateral interviews with expert stakeholders

Semi-structured interviews were held with a wide range of expert stakeholders, including HHP manufacturers, controls developers, industry associations, academics and other technical experts. A list of the stakeholders consulted is provided below.

- Andy Green, Baxi
- Jeff House, Baxi
- John Mulcahy, British Gas (Hive)
- Adrian Richardson, British Gas (Hive)
- Savvas Tassou, Brunel University
- Tom Garrigan, BSRIA
- Richard Paine, Daikin
- Graham Wright, Daikin & UK Heat Pump Association
- Peter Wagener, Dutch Heat Pump Association
- Stuart McKinnon, Energy Systems Catapult
- Marek Miara, Fraunhofer Institute
- Rob Gardiner, G-Core
- Martin Betz, Glen Dimplex
- Chris Davidson, Ground Source Heat Pump Association
- Svend Pedersen, Heat Pumping Technologies
- Stewart Clements, Heating & Hot water Industry Council (HHIC)
- Craig Kaminsky, Home Group
- Mark Johnson, Joule UK
- Guy Cashmore, Kensa
- Max Halliwell, Mitsubishi Electric
- Adrian McLoughlin, Newcastle City Council
- Phil Hurley, NIBE
- Chris Underwood, Northumbria University
- Ian Rose, PassivSystems
- Edwin Carter, PassivSystems
- Dave Pearson, Star Refrigeration / Neatpumps
- Nick Salini, Thermal Earth
- Christian Engelke, Viessman
- Oliver Lancaster, Wales and West Utilities
- Bob Critoph, Warwick University
- Mitchell Cogger, Worcester-Bosch

Analysis of field-trial data

A dataset from a recent independent field trial of 550 HP systems in Manchester, including 89 packaged air-source HHPs, was made available by BEIS for the purposes of this analysis. Given the relative shortage of in-situ HHP field trial data from the UK, this was a valuable source of data on HHP performance. Data was only available for 429 of the 550 sites.

The data was analysed to enable a comparison of the findings of the literature review, expert consultation and technical modelling (see below) with the real-world evidence from the field trial. Further details of the field trial are presented in the Appendix. The key findings of relevance to this study are provided in Section 5.1 and in comparison with the outputs of the technical modelling in Sections 6.2 and 6.3.

Technical modelling

A key component of this study is an original technical modelling exercise to examine the performance of HHPs in a wide variety of configurations, building types and climatic conditions. It was expected that the literature review, stakeholder consultation and analysis of field-trial data would give rise to a limited number of datasets on the current in-situ performance of HHP in the UK, given the relatively immature status of the HHP market. In order to supplement the evidence collected through these methods, an extensive original technical modelling exercise was undertaken to study the factors influencing the performance of HHPs. This made use of existing tools within the project team, including Eider Consulting's suite of REFPROP-based thermodynamic models and Element Energy's half-hourly heating demand simulation model. The details of the modelling approach and key outputs from the exercise are presented in Section 6.

3 Factors influencing cost and performance of domestic HHPs

The configuration of hybrid heat pump (HHP) systems can vary according to numerous parameters. Many of these parameters affect the physical requirements of the product itself, and as such will impact the upfront cost. Other parameters, including the operating conditions, may not have a significant impact on cost, but will affect the efficiency of the heat pump and will therefore impact the different performance parameters: namely the share of the demand met by the heat pump, the CO_2 emissions savings compared to a boiler, and the peak electricity demand.

Table 3-1 shows the various parameters that distinguish HHP systems addressed in this analysis.

Table 3-1 HHP parameters

PARAMETER	EXAMPLES
Type of heat pump	Air source monobloc; air source split
Hybrid configuration	Add-on to existing boiler; integrated boiler and heat pump (one product); packaged boiler and heat pump (separate products)
Heat pump size	Oversized relative to heat demand; undersized relative to heat demand
Heating schedule	Twice a day; continuous
Domestic hot water provision	Boiler meets DHW demand; heat pump can contribute to DHW demand
Thermal store	No thermal store; large hot water-based thermal store
Hybrid mode	Switch; parallel
Control strategy	External temperature set point; economic optimisation;
Type of emitters	Standard (high temperature); low temperature
Building type	Efficient semi-detached; high heat loss detached; new build flat

The next sections describe each of these parameters in more detail, and discuss their particular impacts on cost and performance.

3.1 Type of heat pump

For the purposes of this study, a HHP is defined as one combining an electrically-driven heat pump with a gas boiler, along with a dedicated controller. The HHPs currently on the market consist of some configuration of an air-source heat pump, a boiler, and a controller. Air-source heat pumps (ASHPs) and their hybrids fall into the following basic categories:

- Monobloc: heat pump is a single unit, usually mounted outside.
- Split: heat pump has an outdoor unit including the outdoor heat exchanger and the compressor, and an indoor unit including the indoor heat exchanger.

Ground-source heat pumps (GSHPs) currently tend to be installed in commercial buildings and large domestic properties, either in new buildings or as part of extensive retrofits bringing the building up to high energy efficiency standards. According to manufacturers and installers, they are unlikely to be used in a hybrid configuration, as their high efficiency and ability to store heat negates the potential cost and peak-shaving benefits of hybrid systems. The performance of GSHPs can be superior to those of ASHPs (both in terms of peak electricity demand and in terms of emissions benefits), but they also have higher capital costs and require ground loop installation, which can be inconvenient for some users.

3.1.1 Impact on performance

There is no significant difference between the performance of monobloc and split air-source heat pumps. Some manufacturers now offer inverter-driven heat pumps, which have variable compression rates and reportedly operate more efficiently over a wider range of operating conditions, compared to non-inverter driven heat pumps. Monobloc heat pumps are now also available in 'compact' designs which have a smaller footprint compared to non-compact versions, and would therefore be more practical in terms of installation and any required planning permissions.

3.1.2 Impact on product cost

According to consulted stakeholders, monobloc and split heat pumps have very similar product costs.

3.1.3 Summary

Table 3-2 summarises the extent of the impacts of heat pump type.

Table 3-2 Impacts of heat pump type on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Type of heat pump	• Air source Monobloc • Air source split	• LOW	• LOW

3.2 Hybrid configuration

Based on previous research and conversations with manufacturers, the following hybrid configurations can be defined:

- Add-on: heat pump and controller installed to work alongside an existing boiler;
- Integrated: boiler, heat pump and controller sold and installed together as one product;
- Packaged: boiler, heat pump and controller available as separate products but sold and installed together.

3.2.1 Impact on performance

While the performance of heat pumps may vary between different manufacturers, according to the consulted stakeholders there is unlikely to be a significant difference to overall performance between the different hybrid configurations, provided that the installation has been to a high standard and the controller has the same capabilities. For 'add-on' cases where the existing boiler is not replaced, there may be some efficiency losses for the share of heat met by the boiler, compared to a hybrid system with a new boiler. However, considering that the heat pump is intended to meet the majority of the heat demand in a hybrid system, small differences to boiler efficiency are unlikely to make a significant difference to the overall efficiency of the system and the associated emissions.

3.2.2 Impact on product cost

According to manufacturers and other stakeholders (including organisations with experience of installing hybrid systems), there is unlikely to be a significant cost difference between different hybrid configurations. Cases where a heat pump is installed as an 'add-on' to an existing boiler would technically avoid the cost of a new boiler, but this would theoretically need to be replaced at some point during the lifetime of the heat pump.

3.2.3 Summary

Table 3-2 summarises the extent of the impacts of hybrid configuration.

Table 3-3 Impacts of hybrid configuration on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Hybrid configuration	• Add-on to existing boiler • Integrated boiler and heat pump (one product) • Packaged boiler and heat pump (separate products)	• LOW	• NONE - LOW

3.3 Heat pump size

The heat pump size (or rated thermal capacity) determines the maximum heat output that can be provided by the heat pump. This varies according to the external temperature and the required output flow temperature, so the 'rated' capacity (measured under certain conditions) will not necessarily be the absolute limit of the possible heat output.

3.3.1 Impact on performance

The in-situ performance of a HHP system varies depending on how the rated capacity of the heat pump component compares to the maximum heat demand of the building. According to manufacturers of HHPs, the ideal share of the overall heat demand met by the heat pump versus the boiler would be between 70:30 and 85:15. An 'oversized' heat pump would have the capacity to meet the entire annual heat demand, potentially increasing the emissions savings relative to the 85:15 case (depending on the operating conditions). An 'undersized' heat pump would meet less than 70% of the overall heat demand, reducing the emissions savings, but also reducing the peak electricity demand (as this would be shifted to the gas boiler). Between these two cases, the sizing of the heat pump would still impact the emissions savings and peak electricity demand, but the operating conditions would also play a major role (see sections 3.4 to 3.10).

3.3.2 Impact on product cost

Heat pump cost varies according to thermal capacity, and therefore sizing has a significant impact on the cost of a hybrid system. Specific costs are discussed in Chapter 4.

3.3.3 Summary

Table 3-4 summarises the extent of the impacts of heat pump size.

Table 3-4 Impacts of heat pump size on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Heat pump size (relative to heat demand)	• Oversized • Midsized • Undersized	• HIGH	• MEDIUM-HIGH

3.4 Heating schedule

A heating schedule defines the times at which the heating system of a building is used to raise its internal temperature to the temperature desired by the occupants (i.e. the target temperature). In the UK, the majority of households (73%) report that they heat their homes in a regular manner (i.e. they turn their heating on and off at set times of the day, even if this might vary for different days of the week), and 70% of centrally heated households report that their heating comes on twice a day (with an additional 21% reporting that their heating comes on once a day). A **twice a day** heating schedule involves heating for up to 4 hours in the morning at a 'wakeup time' and then again at 'home-time' for 4-10 hours.[6] This results in the building temperature rising rapidly in the morning to meet the target temperature, dropping slightly during the day when the heating is turned off, then rising again at 'home-time'. On cold winter days, depending on the thermal efficiency of the building, the temperature can drop very low when the heating is turned off overnight, meaning that the heating system has to work hard to achieve the target temperature in the morning.

An alternative heating schedule is **continuous** heating. In this case, the heating is kept on constantly throughout the day. The target temperature (and therefore the heat output) is likely to be lower overnight than it is during the day, but during the heating season, the building will be kept above external temperature throughout each 24 hour period. This means that the heating system will never have to work as hard as it would in the twice a day heating case.

3.4.1 Impact on performance

In the absence of thermal storage, the performance of standalone heat pumps and HHPs is strongly dependent on the heating schedule followed, with the optimal performance being achieved for continuous heating, and a twice a day heating schedule being the worst case scenario in terms of performance. For the standalone heat pump case, this is because the heat pump cannot operate at the high flow temperatures which would be required to deliver the high level of heat demand at the morning peak, particularly during the colder months of the heating season. In addition, the power requirements at peak times would exceed the maximum output of a heat pump (sizing is usually based on a

[6] BRE for DECC, "Energy follow-up survey 2011, Report 4: Main heating systems", 2013

more continuous profile, which allows the heat pump to operate more efficiently). This means that the resistive heater installed alongside the heat pump has to work to meet the heat demand for a significant part of the daily heating profile, and this reduces the overall efficiency of the system. In addition, the resistive heater would have a high electricity demand at peak times, corresponding to the high peaks in heat demand. As well as causing a significant increase to the peak domestic power consumption, depending on the domestic power limit, the heater may not be able to draw enough power to meet the very high peaks in heat demand, resulting in a loss to comfort.

For HHPs, where the heat pump component would typically be slightly smaller than for an equivalent standalone system, the impact of a twice a day heating schedule would be similar; the heat pump would be unable to provide sufficient heat at the daily peak in the winter months, and this would be met by the boiler component, thus significantly reducing the potential emissions benefits of the heat pump system. However, the advantage of the hybrid system over a standalone system for the twice a day case would be that the effect of the boiler taking over would be to eliminate (or significantly reduce) the power consumption at these times.

For both the standalone and HHP cases, continuous heating enables heat pumps to operate at a relatively low, relatively constant temperature, which maximises the efficiency of the heat pump, the share of heat demand met by the heat pump, and the associated emissions benefits. In addition, the peak electricity demand seen by the heat pump over the course of the year would be reduced.

The performance impacts of heating schedule could be mitigated by using storage (see Section 3.6.

3.4.2 Impact on product cost

The heating schedule has no impact on the upfront cost of a HHP. However, due to the impacts on performance it is likely to affect the operating costs.

3.4.3 Summary

Table 3-5 summarises the extent of the impacts of heating schedule.

Table 3-5 Impacts of heating schedule on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Heating schedule	• Twice a day • Continuous	• NONE	• HIGH • Heat pump performance is better with continuous heating

3.5 Domestic hot water provision

There are two main options that are typically considered for domestic hot water (DHW) provision in a HHP system. The first is that the boiler meets the whole DHW demand. Many homes now have combi gas boilers, which can provide DHW on demand without the need for a hot water cylinder. A combi boiler is a practical choice for the boiler component of a hybrid system, as it dispenses with the need for a hot water cylinder and therefore reduces the overall space requirements of the system. For example, Daikin's integrated HHP package (sold as a unit, including the boiler) includes a combi boiler.

The second option is that the heat pump component can contribute to meeting the DHW demand, with the boiler component topping up any demand that cannot be met by the heat pump. In theory, the heat pump could contribute without a hot water cylinder, but in practice, DHW is produced at times where the space heating demand is lower, and stored in a hot water cylinder until it is needed. This enables the heat pump to meet as much of the demand as possible without operating at high (and inefficient) flow temperatures.

3.5.1 Impact on performance

When the boiler component is used to meet DHW demand, the heat pump is only required to meet the space heating demand. As such, performance will depend on the heating schedule for space heating, as described in section 3.4. Emissions will depend on the overall share of demand accounted for by DHW (between 10% and 20% for the majority of UK homes, or around 30% for highly efficient new build homes). In the future, the typical share of demand for DHW is likely to increase as the efficiency of homes increases (alongside any increases in average external temperatures as a result of climate change), in which case (assuming there is no significant change to the carbon content of gas) the emissions savings achieved by HHPs where the boiler meets the DHW demand could be significantly reduced.

If the heat pump contributes to meeting DHW demand, this would be likely to reduce the overall efficiency of the heat pump, as well as increasing the average and peak electricity demand. If the DHW demand is spread throughout the day, for a continuous heating schedule the DHW and space heating demand will coincide, resulting in an increased load and an increased flow temperature compared to that required to meet the space heating demand. This will reduce the COP of the heat pump. Also, the temperature for DHW is at least 40 degrees Celsius[7], which is above the optimal flow temperature of a typical air-source heat pump, meaning that even if there is no space heating demand, the heat pump will be operating to meet the DHW demand under non-optimal conditions.

Due to these factors, several manufacturers selling HHPs shared the view that in a hybrid configuration, using the boiler to provide DHW is the most practical option, and that using the heat pump for this would not be recommended.

3.5.2 Impact on product cost

For the case where the boiler component of a hybrid system provides DHW, there would be no additional cost. As mentioned above, if the heat pump is to provide DHW, a hot water cylinder for storage would be required alongside the hybrid system. In theory, an existing hot water cylinder could be used for this purpose, but most manufacturers recommended replacement with a cylinder more suited to operation with a heat pump. For example, hot water cylinder with a capacity of 100 litres would cost in the region of £200.

3.5.3 Summary

Table 3-6 summarises the extent of the impacts of domestic hot water provision.

[7] To prevent Legionella, any stored water would need to be briefly raised to a temperature of 60 degrees Celcius at least once a day. In a hybrid system, this would be done by the boiler, and for a standalone heat pump this would be done by the resistive heater.

Table 3-6 Impacts of domestic hot water provision on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Domestic hot water provision	• Boiler-only • Heat pump or boiler	• LOW-MEDIUM • Additional cost for hot water cylinder to enable heat pump provision of DHW	• HIGH • Higher efficiency and lower peak demand for boiler-only case

3.6 Thermal store

A thermal store enables heat to be stored for a period of time, and used when required. This allows the demand profile seen by a boiler or heat pump to be smoothed or otherwise manipulated. For example, hot water cylinders are used to store hot water, which allows the daily demand on the hybrid system to be spread out over the day. Most domestic thermal stores currently involve the storage of hot water, but other forms of thermal storage with higher energy densities are also available. These offer a high storage capacity in a more compact form than would be possible with hot water storage. Currently, high energy density thermal storage (e.g. using phase change materials) costs in the region of 250-400 £/kWh and is at a relatively early stage of product development therefore is rarely used in domestic heating systems. However, costs are likely to come down to the lower end of this band within the next five years, and if this trend continues, the technology could work well to improve the performance of heat pumps or HHPs[8].

3.6.1 Impact on performance

Heat pumps are most efficient when operating continuously at low temperatures. This presents a challenge for operation in UK homes, where the most common mode of heating involves daily peaks in heat demand requiring high flow temperatures (as discussed in section 3.4). However, in a system with an appropriately sized thermal store, the heat demand in any given half hourly or hourly period can be met using heat from the store, providing that the emitters have an appropriate capacity, and that the store has been sufficiently filled in advance. In this case, the demand seen by the heating system would be whatever is required to keep the store adequately charged; this could be spread evenly throughout the day, thereby smoothing the peaks in demand and reducing the peak electricity demand. In a hybrid system (where the boiler would normally meet the high peaks in demand in winter months), this would maximise the overall share of heat demand met by the heat pump. We note that, unless the heat schedule practised by the consumer also changes, the flow temperatures required at the radiators would not be modified, meaning that the thermal store would need to store heat at a high enough temperature to meet the peak demand at the radiators.

Currently, a hot water-based thermal store with enough capacity to significantly smooth a twice a day heat demand profile on a winter day (e.g. 500-1000l) would have a prohibitively large footprint for many UK households. A lower capacity store could still bring slightly smoother demand profile for the heat pump and the associated improvements to performance, but higher density, high capacity thermal storage would achieve more with a

[8] Evidence Gathering: Thermal Energy Storage (TES) Technologies, Delta Energy & Environment Ltd. for BEIS, 2016.

smaller footprint and would ultimately be a more practical solution to improve the performance of heat pumps or HHPs.

If storage could be used to smooth the electricity demand from a heat pump to an almost constant level, this would substantially reduce the peak electricity demand. This could hypothetically negate the need for a HHP in many cases. However, for most UK homes the storage solution would depend on significant cost reductions in high density thermal storage, whereas HHPs could already offer a practical way to reduce peak electricity demand.

3.6.2 Impact on product cost

The cost of thermal storage would be strongly dependent on the capacity required, and on the type of storage used. For example, a hot water tank with sufficient capacity to smooth demand for a typical semi-detached on an average January day (i.e. 500 litres for a storage capacity of around 20 kWh[9]) would cost in the region of £1,500. A high density thermal store (e.g. using phase change materials) with the same storage capacity could cost £5,000-£8,000 at today's prices[10], and would occupy a much smaller volume (e.g. a tenth of that of a hot water tank).

3.6.3 Summary

Table 3-6 summarises the extent of the impacts of including a thermal store in a HHP system.

Table 3-7 Impacts of thermal store on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Thermal store	• No thermal store • Thermal store of various types and capacity	• MEDIUM-HIGH • Additional cost for thermal store, depending on capacity and energy density	• MEDIUM-HIGH • Higher efficiency and lower peak demand for thermal store (benefits increase with capacity)

3.7 Hybrid mode

HHPs, as they are defined in this report, can be distinguished according to whether the heat pump and the boiler ever work to meet the space heating demand (or if relevant, the DHW demand) at the same time. In a 'switch' hybrid mode, if the boiler is required to meet the space heating demand, the heat pump will turn off and the boiler will heat the water to the required flow temperature. In a 'parallel' hybrid mode, the heat pump can contribute to meeting the space heating demand (e.g. providing heat up to the maximum output capacity or the maximum output temperature), and the boiler provides the remaining heat required for the water to reach the right temperature.

[9] To sufficiently 'smooth' a daily space heating demand of 40kWh, a minimum of 20kWh of storage would be needed. Capacity calculation assumes that water is raised from 10 degrees to 45 degrees.

[10] 250-400 £/kWh according to: Evidence Gathering: Thermal Energy Storage (TES) Technologies, Delta Energy & Environment Ltd. for BEIS, 2016.

3.7.1 Impact on performance

In a parallel mode, the overall share of heat demand met by the heat pump is maximised, compared to the switch case, where the boiler provides 100% of the demand if the heat pump capacity is insufficient, or under other conditions specified by the control strategy (e.g. when the temperature drops below a certain point). Depending on the conditions, this could lead to slightly lower heat pump efficiency for the parallel case, as it implies that the heat pump is working at its limit more frequently. Taking these two effects into account, the overall effect on performance in terms of emissions is likely to be fairly marginal, assuming that the heat pump is sized appropriately (i.e. with the capacity to meet the majority of the annual space heating demand).

3.7.2 Impact on product cost

There is no significant difference in product cost according to whether a HHP system operates in switch or parallel mode.

3.7.3 Summary

Table 3-8 summarises the extent of the impacts of the choice of hybrid mode.

Table 3-8 Impacts of hybrid mode on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Hybrid mode	• Switch • Parallel	• NONE-LOW	• MEDIUM • Depending on operating conditions (particularly the heating schedule), there may be some difference in annual emissions between the two cases

3.8 Control strategy

The "control strategy" for a HHP is the term used to describe the basis on which the system decides when to use the heat pump and when to use the boiler (or, in a parallel hybrid mode, what share of the heat demand is met by each mode).

3.8.1 Impact on performance

The simplest control strategy is a **'switch' mode** based on an **external temperature set-point**. In this case, when the external temperature falls below the set-point, the heat-pump will turn off and the boiler will take over. This strategy is intended to prevent the heat-pump from operating at particularly low COPs, at which point it could be more cost-effective (and/or in theory even more low carbon) to provide heat using the boiler.

According to stakeholder interviews, the set-point temperature is usually set by the installer, and may differ depending on the size and energy efficiency of the building it is installed in. Installers select the set-point based on detailed guidance (from manufacturers and MCS), and there is a good chance that a set-point strategy will result in a good balance of heat pump efficiency and fuel cost savings. However, several factors limit the effectiveness of a set-point strategy: a) the accuracy of the building heat demand assessment; b) variability of electricity carbon intensity and fuel prices over the lifetime of the heating system mean that a fixed temperature set-point would not enable a consistent optimisation of either carbon intensity or emissions.

One alternative to using a set-point strategy could be **fuel cost-optimisation**, whereby the heat pump turns on or off according to whether it would be cheaper or more expensive to run than the boiler. In the simplest version of this case, the installer (or the user) can pre-program the heat pump controller with a fixed gas and electricity tariff, which inform the optimisation. A few manufacturers already have this option for integrated or packaged HHPs. However, a more advanced controller could allow "smart" updating of the tariffs and would therefore be able to ensure that the overall fuel cost is minimised, even when electricity tariffs change. This could also enable the heat pump to respond to dynamic electricity pricing (whereby prices vary through the day on an hourly or half hourly basis).

Although dynamic or "time-of-use" electricity pricing is not yet in place for domestic electricity consumers in the UK, the UK government recently published a strategy for smart systems and flexibility, which includes plans to encourage more domestic demand response through half-hourly settlement and, for example, "smart tariffs"[11]. The ability of HHPs to respond to dynamic pricing could be one way to reduce the additional load from heat pumps at times of peak electricity demand; DNOs could discourage domestic customers from using the heat pump component at these times by temporarily increasing the network use of systems charge (DUoS). Alternatively, smart controllers could enable heat pumps to respond to load control signals (e.g. from the DNO or from an aggregator), to temporarily reduce (or even increase) the heat pump output according to the needs of the local grid. The FREEDOM project (which began in September 2016) is a large-scale demonstration trial of smart hybrid heating systems, which will trial HHPs with smart controls in around 70 dwellings, and will test their performance under various control strategies by simulating different time-of-use pricing mechanisms and grid-based signals from the distribution network operator, Western Power Distribution.

CO_2 optimisation could work in a similar way, to maximise CO_2 savings. A simple mode could use programmable (fixed) assumptions about the CO_2 intensity of the electricity powering the heat pump (i.e. from the grid or on-site generation) and the natural gas powering the boiler, combined with information on the heat pump efficiency at different external temperatures, to determine when the heat pump should be switched on or off to minimise the carbon emissions produced. A "smart" controller could theoretically enable further reductions to overall emissions by accessing live data on carbon intensity (e.g. from the grid, or regarding the available electricity from onsite generation) to inform a more dynamic (and therefore more accurate) optimisation. However, this would rely on the accessibility of this data for domestic users.

Advanced controllers could also combine economic and CO_2 optimisation. For example, an end-user could choose to optimise for CO_2 as long as the cost per kWh remains below a certain level. Support mechanisms such as the RHI could also be accounted for in such optimisations[12].

[11] See p 15 of: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/633442/upgrading-our-energy-system-july-2017.pdf

[12] Support for hybrid heat pump systems under the Domestic RHI requires metering in order to calculate the renewable share of heating (unlike electric-only heat pumps where deemed heat output can be applied), so the RHI could be factored into the consumer's economic optimisation.

3.8.2 Impact on product cost

According to manufacturers and other consulted stakeholders, for a heat pump using an **external temperature set-point** control strategy, the controls (and associated costs) will be included in the product cost of the HHP (even in the case where the heat pump is sold as an “add-on” to an existing boiler), so there is no additional cost. Where available, controls allowing simple cost-optimisation and/or CO_2-optimisation also tend to be included in the product costs.

At the time of the consultation, one or two manufacturers were in discussions with potential suppliers of smart controls with functionality outlined above. Based on their input, the additional costs associated with incorporating smart controllers would be low (e.g. around £100-200). Passiv Systems are currently trialling a smart control unit as part of the FREEDOM project, which enables the optimisations described above and is available for around £300 per unit.

3.8.3 Summary

Table 3-9 summarises the extent of the impacts of the control strategy.

Table 3-9 Impacts of control strategy on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Control strategy	• External temperature set-point • Fuel cost-optimized • CO_2-optimized • Grid-signal responsive	• LOW • Simple controls often included in heat pump costs	• HIGH • Smart controls could maximize potential to reduce peak electricity demand and / or maximize efficiency and CO_2 emissions savings

3.9 Type of emitters

The majority of existing domestic properties in the UK have central heating systems with gas boilers and **high temperature emitters**, for which the typical design flow temperatures are 80ºC flow and 60ºC return (‘80/60’). Conversely, the typical maximum output temperature used in most domestic heat pumps and hybrids is of the order 55ºC[13]. This means that in general, a heat pump combined with emitters sized for 80/60 may not be capable of providing sufficient heat to the building at times of peak heat demand. Standalone heat pump systems are therefore frequently installed with **low temperature emitters,** which are ‘oversized’ relative to 80/60 emitters and are able to meet the same heat demand at lower flow temperatures. Low temperature emitters include underfloor heating, as well as larger radiators.

In the case of HHPs, the boiler component provides the capability of meeting the peak heat demand with higher flow temperatures (above 55ºC). Therefore, low temperature emitters are not necessarily required. HHPs can either be installed alongside existing high temperature emitters, or with low temperature emitters.

[13] Although it is possible for heat pumps to supply heat at temperatures as high as 80ºC or 90ºC, this is not typical for domestic installations.

3.9.1 Impact on performance

As mentioned above, if the HHP is working with high temperature emitters, the gas boiler component can be used to supply the higher flow temperatures, either in parallel with the heat pump (increasing the temperature from 55ºC to 80ºC) or, in switch mode, instead of the heat pump. This ensures that comfort can be achieved. However, the disadvantage of this is that it limits the fraction of the heating demand that can be supplied by the heat pump – limiting the potential carbon emissions reduction, for example. The severity of this limit will depend on the thermal efficiency of the building and the external temperature. For the case with low temperature emitters, more of the heat demand can be met by the heat pump, which could increase the potential carbon emissions reduction.

Low temperature emitters would also reduce the average electricity demand from the heat pump, compared to the case with high temperature emitters, as the heat pump will be operating more efficiently overall at the lower flow temperatures required. This could also reduce the peak electricity demand, although this is also dependent on how much of the heat demand is met by the heat pump component in each case.

3.9.2 Impact on product cost

The total cost differential for high temperature versus low temperature emitters partly depends on the type of low temperature emitters; a retrofit of the building to install underfloor heating is likely to be more costly than installing large radiators. However, the key factor is whether the building already has a central heating system: if so, then the consumer could avoid the costs of installing low temperature emitters by using the existing high temperature emitters. Depending on the heating requirements in different rooms, in a centrally heated building the consumer could also choose to only replace one or two high temperature radiators with low temperature radiators. The range of associated costs is explored in Chapter 4 of this report.

Conversely, if the heat pump or HHP system is replacing electric radiators, the entire central heating system would need to be installed and the cost differential between high and low temperature emitters would be much smaller.

3.9.3 Summary

Table 3-10 summarises the extent of the impacts of the type of emitters.

Table 3-10 Impacts of type of emitters on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Type of emitters	• High temperature • Low temperature	• MEDIUM • Cost savings if existing emitters are used	• HIGH • Low emitters improve COPs and reduce peak electricity demand

3.10 Building type

Along with the heating schedule, the thermal efficiency and size of a building are fundamental factors determining its annual and daily heat demand profile. As buildings increase in size, the heat required to raise their internal temperature also increases, and buildings with low thermal efficiency are inherently worse at retaining heat than those which are well insulated, meaning that more energy is required to raise the temperature over the same period of time. Heat pump performance depends heavily on the heating profile, making building type a key determining factor.

3.10.1 Impact on performance

In general, heat pumps work most efficiently with smooth heating profiles (i.e. those where the peak heat demand is relatively close to the average heat demand), as this allows them to operate at low flow temperatures. Buildings which are either small or highly thermally efficient require less heat to raise the internal temperature, and therefore are likely to have 'smoother' daily profiles, compared to larger, less efficient buildings.

These factors mean that in terms of overall efficiency and emissions, the performance of HHP systems is likely to be best for small, efficient buildings. However, for extremely efficient buildings with very low peak levels of heat demand, hybrid systems may not offer significant advantages over standalone heat pump systems; indeed, in such cases electric resistive heating, may be the most cost-effective way to heat the building, rather than a heat pump. In such cases, the ratio between hot water and space heating demand and the selected strategies for meeting each of these are likely to be influencing factors in determining the pros and cons of hybrids versus standalone heat pumps.

3.10.2 Impact on product cost

According to manufacturers and installers consulted as part of this project, the maximum thermal capacity of the heat pump component (and to a lesser extent, the boiler component) of a hybrid system is typically selected according to the typical heat demand seen on cold days, which is directly related to the building type. Since cost varies according to thermal capacity, building type can heavily influence the upfront costs of a hybrid system. In addition, the design and structure of the building and its existing heating system can make a significant difference to installation costs.

3.10.3 Summary

Table 3-11 summarises the extent of the impacts of building type.

Table 3-11 Impacts of building type on cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Building type	Examples: • Semi-detached house with no insulation • Flat with no insulation • Detached house with cavity wall insulation & roof insulation	• HIGH • Building energy demand determines sizing of heat pump and emitters • Building specifics affect installation costs	• HIGH • More efficient buildings will have lower and less variable energy demand, leading to higher heat pump efficiency and lower emissions

3.11 Summary of key influencing factors

Table 3-12 summarises the impact of different HHP parameters.

Table 3-12 Impacts of various factors on HHP cost and performance

Parameter	Options	Impact on product cost	Impact on performance
Type of heat pump	• Air source monobloc • Air source split	• LOW	• LOW
Hybrid configuration	• Add-on • Integrated product • Packaged HP and boiler (separate products)	• LOW	• NONE-LOW
Heat pump size	• Oversized • Midsized • Undersized	• HIGH	• MEDIUM-HIGH
Heating schedule	• Twice a day • Continuous	• NONE	• HIGH • Heat pump performance is better with continuous heating
Domestic hot water provision	• Boiler-only • Heat pump or boiler	• LOW-MEDIUM • Additional cost for hot water cylinder to enable heat pump provision of DHW	• HIGH • Higher efficiency and lower peak demand for boiler-only case
Thermal store	• No thermal store • Thermal store of various types and capacity	• MEDIUM-HIGH • Additional cost for thermal store, depending on capacity and energy density	• MEDIUM-HIGH • Higher efficiency and lower peak demand for thermal store (benefits increase with capacity)
Hybrid mode	• Switch • Parallel	• NONE-LOW	• MEDIUM • Depending on operating conditions (particularly the heating schedule), there may be some difference in annual emissions between the two cases
Control strategy	• External temperature set-point • Fuel cost-optimized • CO_2-optimized • Grid-signal responsive	• LOW • Simple controls often included in heat pump costs	• HIGH • Smart controls could maximize potential to reduce peak electricity demand and / or maximize efficiency and CO_2 emissions savings
Type of emitters	• High temperature • Low temperature	• MEDIUM • Cost savings if existing emitters are used	• HIGH • Low emitters improve COPs and reduce peak electricity demand
Building type	Examples: • Semi-detached house with no insulation • Flat with no insulation • Detached house with cavity wall insulation & roof insulation	• HIGH • Building energy demand determines sizing of heat pump and emitters • Building specifics affect installation costs	• HIGH • More efficient buildings will have lower and less variable energy demand, leading to higher heat pump efficiency and lower emissions

4 Review of cost of domestic HHP systems

As part of this work, we have undertaken primary research on the cost of domestic HHP systems, to supplement and compare with the recent HHP cost and market review undertaken for BEIS in 2016[14]. The cost data was collected through both the literature review and the expert consultation, and the findings are summarised below.

4.1 Product costs

In line with BEIS's 2016 market review on HHPs, our research suggests that HHPs are typically sold in one of three ways, involving the purchase of:

1. An **integrated** HHP system (consisting of HP + boiler + controller in a single unit)
2. An **add-on** HHP system (consisting of HP + controller to supplement either an existing boiler or a boiler purchased separately)
3. **HP**, **controller** and **boiler** separately (where the products may be sold together as a package, but are separate products with individual prices)

The HP component of option (3) is the same product as would be purchased in the case of a standard (electric-only) HP, although the selected size of the HP component may be different in the HHP and HP cases. In the case of both HHPs and standard HPs, additional costs may be incurred for:

- Installation of the HHP or HP system (all cases)
- Purchase and installation of low temperature emitters/radiators (optional for HHP, may not be optional for standard HP)

Where available, we have gathered cost data for each of the individual component for each of these options separately.

We first present the cost data gathered relating to the HP component of the HHP. Given the typical ways in which HHPs are sold, this means:

- For an integrated HHP system: HP + boiler + controller
- For an add-on HHP systems: HP + controller
- For a separate/packaged system: HP only

Figure 4-1 presents a summary of the new cost data collected, indicating the type of HP and the components included. The costs shown *exclude installation costs*, which are presented separately further below. The majority of the cost data collected relates to the 5-16 kW range, with additional data collected for one smaller system of 3.5 kW and one larger system of 22 kW.

Although there is substantial scatter in the costs for similar sized systems, the chart shows a clear reduction in cost in £/kW terms over the size range presented, from more than £1,200/kW for the 3.5 kW system to less than £400/kW for one of the 12 kW systems and the 22 kW system. Most data points are, however, in the range £400/kW to £800/kW, with systems below 10 kW all above £600/kW; systems above 10 kW all below £600/kW.

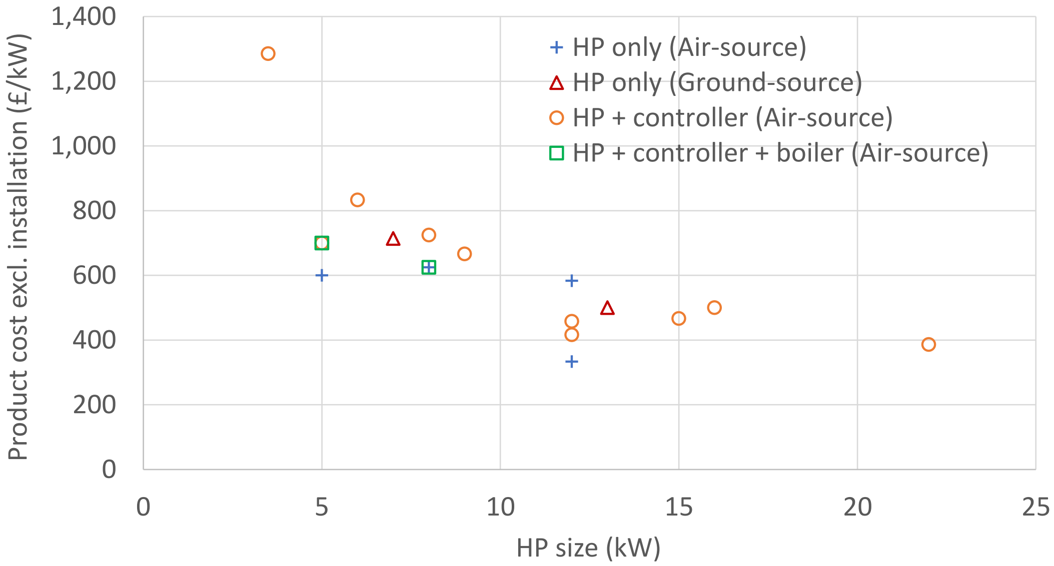
The integrated systems including the controller and boiler do not appear to be significantly higher in cost than the HP only products of a similar size, suggesting that those components are a relatively small share of the overall cost (which is in the region £3-4,000

[14] Carbon Trust for BEIS, *Evidence Gathering – Low Carbon Heating Technologies Domestic Hybrid Heat Pumps*, November 2016.

for the 5 kW system and £5-6,000 for the 8 kW system). A similar finding holds for the add-on systems including the controller, which appear to be only marginally higher in cost than the HP only products of a similar size, a difference within the range of uncertainty on the cost.

Two of the products for which cost data was gathered are ground-source heat pumps; the rest are air-source heat pumps. No significant difference in the cost of these systems compared with the air-source systems of a similar size was observed. It is important to note, again, that these costs do not include installation costs; the installation costs for air-source and ground-source systems were found to be very different, as presented below.

Figure 4-1 Heat pump and hybrid heat pump product cost data (excluding installation cost). 'HP only' costs are for standalone heat pumps which could form potentially form part of an 'add-on' HHP; 'HP + controller' costs also include the controller; 'HP + controller + boiler' costs show the full product costs associated with a HHP system.



The majority of the cost data collected for HHP controllers relate to add-on or integrated systems. However, one stakeholder was able to provide separate cost data for a controller product. The cost of the controller alone was given as within the range £250-350.

Cost estimates for the purchase of a separate gas boiler, excluding installation, are readily available, and are typically of the order £800 for a 24 kW boiler and £1,200 for a 32 kW boiler.

Table 4-1 summarises the product cost data described above, presenting the range of costs gathered for three size categories (<5 kW, 5-11 kW and >11 kW) suggested by the raw data.

Table 4-1 Summary of product cost data (excluding installation cost)

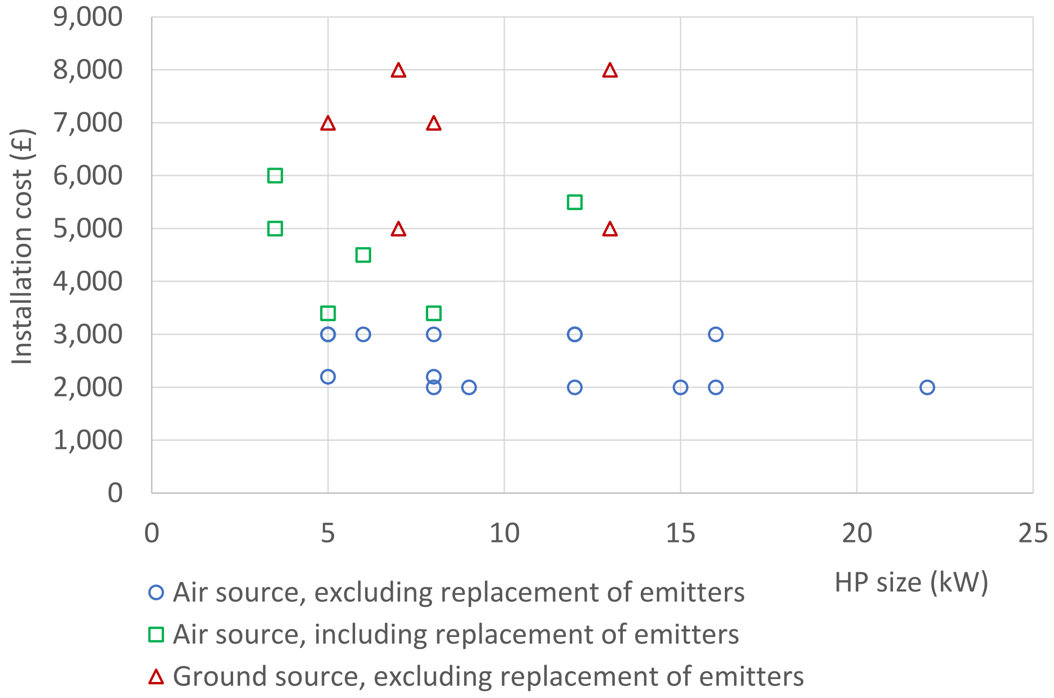
HHP system type	< 5 kW_{th}			5-11 kW_{th}			> 11 kW_{th}		
Integrated (costs shown are for whole system)	HP + Boiler + Controller (£/kW)			HP + Boiler + Controller (£/kW)			HP + Boiler + Controller (£/kW)		
Number of sources	*No products identified*			*2*			*No products identified*		
Minimum				625					
Mean				663					
Median				663					
Maximum				700					
Add-on (costs shown are for the specified components)	HP + Controller (£/kW)		Boiler (£/unit)	HP + Controller (£/kW)		Boiler (£/unit)	HP + Controller (£/kW)		Boiler (£/unit)
Number of sources	*1*			*4*		*1*	*5*		
Minimum	1,285			667		640	386		
Mean	1,285		800-1,200	731		770	446		800-1,200
Median	1,285			713		770	458		
Maximum	1,285			833		1,100	500		
Packaged (costs shown are for the specified components)	HP (£/kW)	Controller (£/unit)	Boiler (£/unit)	HP (£/kW)	Controller (£/unit)	Boiler (£/unit)	HP (£/kW)	Controller (£/unit)	Boiler (£/unit)
Number of sources	*No products identified*			*3*	*1*		*3*	*1*	
Minimum				600	250	800-1,200	333	250	800-1,200

Mean		646	300		472	300	
Median		625	300		500	300	
Maximum		714	350		583	350	

4.2 Installation and emitter replacement costs

Cost estimates for the installation of HHP systems were also collected. A scatter plot of the installation cost estimates gathered, indicating the type of HP and whether the cost includes replacement of emitters, is presented in Figure 4-2.

Figure 4-2 HHP installation cost data (excluding product cost)



The data gathered suggests that the installation cost does not vary significantly with system size over the range examined, from 3.5 kW to 22kW. For the installation of an air-source HHP system, all cost estimates gathered were in the range £2,000 to £3,000, with a mean estimate of £2,600.

The key determinant of the installation cost is whether the HP is air-source or ground-source, and whether replacement of emitters is required. Installation of a ground-source HHP is significantly more costly as a result of the extensive groundworks required. The cost estimates for ground-source HHP installation ranged from £5,000 to £8,000, with a mean estimate of £6,700.

For installations including replacement of emitters, a wider range of cost estimates was observed, from £3,400 to £6,000, with a mean of approximately £4,600. This suggests that the additional cost of emitter replacement is in the range £1,000 to £3,000, with a mean estimate of approximately £2,000. This estimate is quite consistent with separate data from *Which?*[15], which gives the cost of supply and installation of a single radiator as £180. A typical semi-detached house may be expected to require up to approximately ten radiators, leading to an overall cost for replacement of emitters in the region of £1,800.

[15] https://local.which.co.uk/advice/cost-price-information-boiler-repair-central-heating (Accessed August 2017)

Cost estimates for the installation of a gas boiler are available from a *Which?* review[16], and range from £640-£770 for installation of a condensing boiler in the same location as an existing boiler, to £1,140-£1,440 for installation of a condensing boiler in a new location, including an upgrade of radiator valves and controls.

4.3 Maintenance costs

The consensus among experts interviewed was that there is no significant difference in annual maintenance costs for a HHP versus a gas boiler. Annual maintenance cost estimates ranged from £120 to £200.

4.4 Future cost scenarios and impact of innovation and learning

The expert stakeholder interviews were also used to elicit information on the potential for innovation and technological improvement to drive cost reductions in HHPs, whether product cost reductions or installation cost reductions. Stakeholders were asked, where possible, to link the potential cost reductions to the deployment level (of HPs or HHPs) under which this reduction could be realised. The information derived in this way is summarised below. This information was also used to develop a range of scenarios for HHP cost over the period to 2050.

4.4.1 Product cost reductions

The information provided by stakeholders on product cost is summarised in Table 4-2. Responses were generally fairly high level and in most cases did not refer to specific dates by which cost reductions could be achieved, or specific deployment levels required, reflecting the uncertainty on this topic. However, many stakeholders suggested that product cost reductions in the range 10-40% could be achieved, typically citing annual sales of several times the current HP market or, alternatively, in the 100,000s, as the deployment level under which these reductions could occur. The driver for the reduction was variously cited as the impact of greater volumes on compressors, on the hardware more generally, or from simplification of standards. One stakeholder suggested that costs were likely to stay relatively stable, with the market instead developing to produce improvements in performance and product design for the same cost.

Table 4-2 Selected expert comments on potential product cost reductions

Expert comment	Potential cost reduction	Deployment levels under which this could be realised
Manufacturing at greater scale could lead to cost reductions in compressors and HP circuitry	30-40% on product cost	Annual sales of HPs/HHPs in the 100,000s
Hardware cost reduction of £1,000 could be achievable	£1,000 on product cost	Not specified
Product costs are unlikely to reduce as efficiency requirements are always increasing, offsetting gains	None	None

[16] http://www.which.co.uk/reviews/boilers/article/the-cost-of-installing-a-boiler (Accessed August 2017)

Product cost reduction of 30% could be achievable	30% on product cost	Tripling of the current HP market (currently of the order 15,000 per year)
Highly uncertain, but cost reductions of 30% might be possible	30% on product cost	Not specified
A more effective approach than reducing the product cost would be to improve the design such that installation becomes more straightforward (through integrated/'plug-and-play' products), reducing installation cost.	Not applicable	Not applicable
Single digit reductions in product cost could result from greater deployment, due to improved efficiency in both hardware and software	10%	Not specified
For cost reductions to be achieved, regulation would need to be aligned more closely with EU and global standards on electrical safety, test standards and thermal performance	Not specified	Not specified
MSC is currently over-complicated and means cost reductions will be difficult to achieve	Not applicable	Not applicable

Based on these, we have developed three scenarios for product cost reduction to 2050, as shown in Table 4-3. In the High reduction scenario, annual sales increase to the 100,000s, and remain at this level through the 2020s, leading to a 30% cost reduction by 2030, with costs stable thereafter. In the Central scenario, this level of deployment is delayed until the late 2020s, leading to a slower reduction in cost reaching 17% by 2030 and 30% by 2040. In the Low scenario, costs remain at the current level, whether due to little or no increase in annual sales, or due to costs remaining stable while product quality and efficiency improve instead.

For comparison, the Sweett Group's 2013 research on heat pump technologies for DECC presented potential cost reductions for air-source heat pumps to 2030 in the range 5-20%, depending on the learning rate assumed. These cost reductions were associated with an increase in the annual market for HPs by 2030 to 1.8 GWth of air-to-water heat pumps. Assuming, for argument's sake, an average size of 8 kWth per unit, this corresponds to approximately 200,000 units installed annually by 2030. This is roughly consistent with the levels suggested to be required to achieve the 17-30% cost reductions by 2030 in our Central and High scenarios.

Table 4-3 Summary of product cost reduction scenarios

Scenario	Product cost reduction compared with 2017 (%)			Description
	2030	2040	2050	
High	30%	30%	30%	Annual sales increase to the 100,000s, and this level sustained through the 2020s, leading to a 30% cost reduction by 2030
Central	17%	30%	30%	Annual sales increase to the 100,000s only by the late 2020s, leading to a 30% cost reduction by 2040
Low	0%	0%	0%	Little to no increase in annual sales versus 2017; alternatively, sales increase but improvements in product efficiency mean prices do not reduce significantly

4.4.2 Installation costs reductions

The information provided by stakeholders on HHP installation cost is summarised in Table 4-4. There was a strong consensus that installation costs could reduce substantially, and that the current installations costs are high due to poor supply chains, a concentration of expertise among a small number of accredited installers leading to a lack of competition, and the shortcomings of current product design which makes installation of HHPs complex and time-consuming.

The installation cost reductions suggested were in the range 10-70%, where at the high end the installation cost for a HHP could become comparable to that for a gas boiler. This case would require a dramatic increase in simplicity of the installation, likely including pre-integration of the HHP components, and in competition among installers. Installation cost reduction estimates in the range 20-50% were most frequently suggested; where states, this was expected to require annual sales in the 100,000s of HPs or HHPs.

Table 4-4 Selected expert comments on potential installation cost reductions

Expert comment	Potential cost reduction	Deployment levels under which this could be realised
Greater sales volume could drive a reduction of up to 25% in installation costs	25% reduction in installation cost	Annual sales of HPs/HHPs in the 100,000s
Installation profit margin is approximately £1,000 – this could be reduced with competitive pressure	Not specified	Not specified
Installation costs could be reduced with greater sales volumes, through improved product design and pre-integration of components.	30-50% reduction in installation cost	Not specified
Installation costs could be reduced by around 20% without a huge increase in sales volumes.	20% reduction in installation cost	Not specified

Greater variety of packaged options on the market could bring installation costs down by up to 30%	30% reduction in installation cost	Not specified
Up to 10% reduction in installation costs as the market becomes less ‘specialist’. This would require greater sales across the UK (not just across Europe).	10% reduction in installation cost	Not specified
Installation costs excluding ground-works (for ground-source) could reduce to the level of boiler install costs	70% reduction in installation cost (estimated)	Annual sales of HPs/HHPs in the 100,000s
Much greater competition among installers is needed. There are currently accredited installers of HPs, compared with 100,000 gas professionals.	Not specified	Not specified
Improved product design, such that installation becomes more straightforward (through integrated/‘plug-and-play’ products), could reduce installation costs by up to around a half.	50% reduction in installation cost	Not specified
Single digit reductions in installation cost could result from greater deployment.	10% reduction in installation cost	Not specified
Integrated HHP systems could have much lower installation cost than current systems – perhaps 60% lower	60% reduction in installation cost	Not specified

Based on these, we have developed three scenarios for HHP installation cost reduction to 2050, as shown in Table 4-5. In the High scenario, annual sales in the 100,000s through the 2020s, combined with improved product design and integration, leads to a cost reduction of 30% by 2030. In the Central case, a lower level of deployment delays the cost reduction, which reaches 17% by 2030 and 30% by 2040. In the Low scenario, little or no change in the market size leads nonetheless to improved capability of the supply chain leading to a small installation cost reduction of 10% by 2030.

Table 4-5 Summary of installation cost reduction scenarios

Scenario	Installation cost reduction compared with 2017 (%)			Description
	2030	2040	2050	
High	30%	30%	30%	Annual sales increase to the 100,000s, and this level sustained through the 2020s, leading to a 30% cost reduction by 2030
Central	17%	30%	30%	Annual sales increase to the 100,000s only by the late 2020s, leading to a 30% cost reduction by 2040
Low	10%	10%	10%	Little to no increase in annual sales versus 2017; small increase in competition leads to 10% cost reduction by 2030

5 Review of technical performance of domestic HHP systems

5.1 Current performance of domestic HHPs

The following section summarises the current performance characteristics of domestic heat pumps on the market today, including HHPs and standalone heat pumps (which are the counterfactual technology but which can also be used as part of 'add-on' HHP systems alongside a boiler). Values shown are based on manufacturer specifications as well as values quoted in other recent studies, including various field-trial reports. In addition, the data from a Manchester-based field trial of over 400 domestic heat pumps (which includes both standalone and HHPs) is presented, showing key results for average and peak electricity demand.

5.1.1 COP of standalone heat pumps and HHPs

Figure 5-1 shows the range of COP values at various test conditions for air-source heat pumps from a range of manufacturers. The 'N' values shown on the bars represent the number of heat pump products included in the mean and range values shown. Figure 5-1 illustrates a number of points about heat pump performance:

- The external temperature is a key factor determining efficiency;
- Heat pump COP can vary considerably between different manufacturers;
- There is no significant difference in COP between the heat pumps in split, monobloc, and hybrid systems.

Figure 5-1 COP of hybrid and standalone heat pumps measured at various test conditions[17]

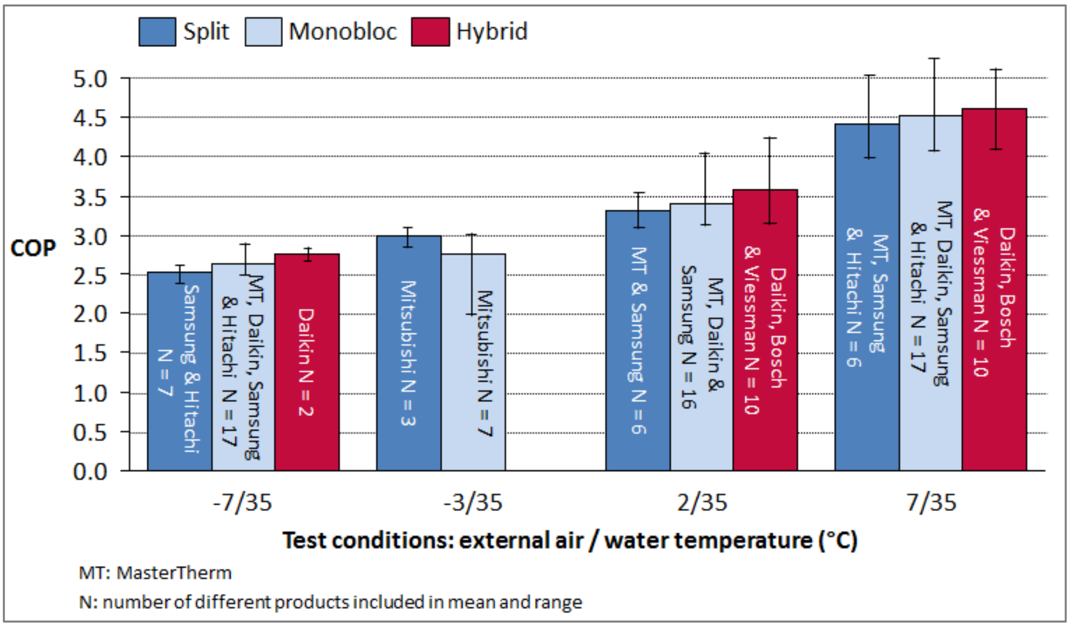
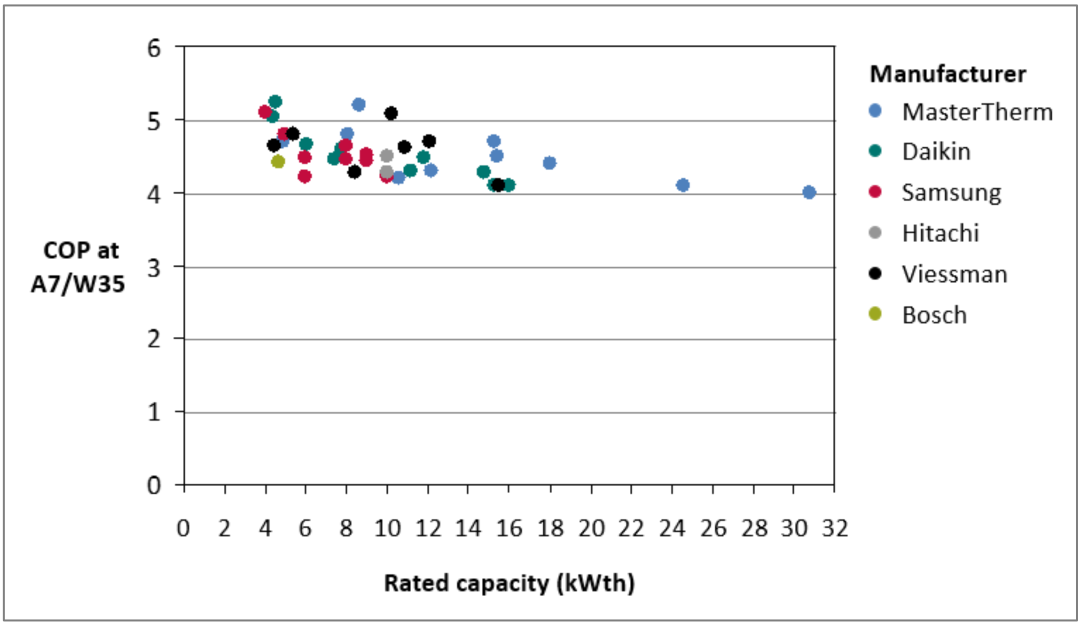


Figure 5-2 shows the full range of COP values measured at A7/W35 for heat pumps of different rated capacity.

[17] Note that the rated COP values for the hybrid systems are for the heat pump component only, i.e. they do not include the gas boiler component.

Figure 5-2 COP of heat pumps by rated capacity (measured at A7/W35)



Based on the values shown in Figure 5-2, heat pump capacity has no significant impact on COP. The range of values is different for each rated capacity, but this is largely to the differences in COP between different manufacturers and the sizes of heat pump offered by each manufacturer.

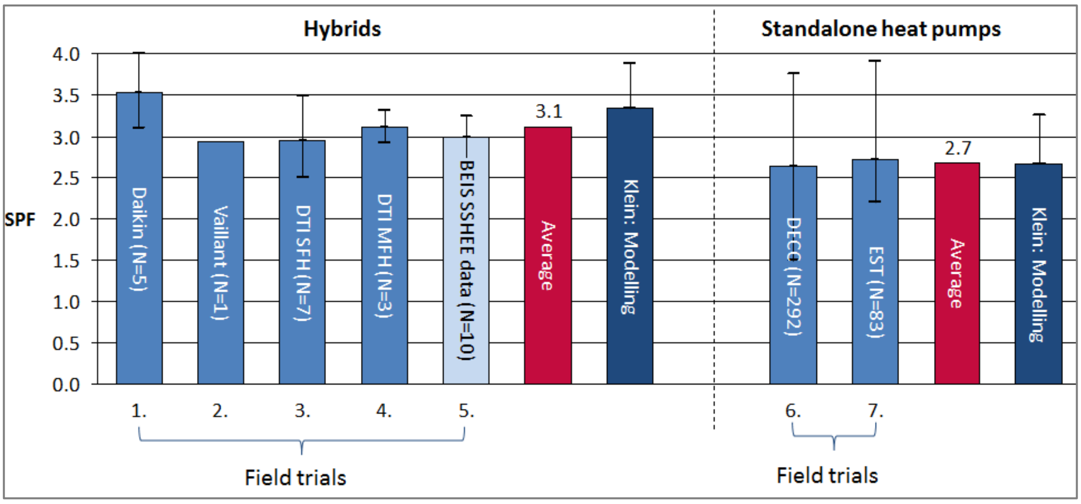
5.1.2 Seasonal performance factors of domestic standalone heat pumps and HHPs

The seasonal performance factor (SPF) of a heat pump is an assessment of the overall efficiency of a heat pump system over a certain operating period, i.e. total heat output over that time period, divided by total electricity in during that period.

Figure 5-3 shows a range of SPF values recorded in various heat pump field trials and modelling work, mainly in the UK. The SPF values shown are calculated based on the work done by the heat pump only (i.e. they do not include energy demand met by the resistive heater in the standalone heat pump case, or the boiler in the hybrid case). Details on the source and conditions for each value are given in the table below the graph. For comparison with the field trial data, the dark blue bars show the results of previous heat pump performance modelling for an existing and a renovated building; the error bar shows the improvement in SPF in the renovated building[18].

[18] K. Klein, K. Huchtemann, D. Müller, Numerical study on hybrid heat pump systems in existing buildings. Energy and Buildings 69 (2014) 193-201.

Figure 5-3 SPF values for standalone heat pumps and HHPs[19]



No.	Source	Monitoring period	HP type	SPF type	Other details
1.	Daikin, 2017	April 2014 - March 2015	5kW hybrid, 8kW hybrid	H1	• HP does pre-heating only; storage tank required - Two bedroom terraced house - Three bedroom semi detached bungalow - Three bedroom semi detached house - Three bedroom semi detached house
2.	Vaillant	Unknown	5kW hybrid	H1	• Single system
3.	DTI, 2015	Oct 2014 - Sept 2015	5kW hybrid	H2	• Single Family Homes
4.	DTI, 2015	Oct 2014 - Sept 2015	25kW hybrid	H2	• 3 Multiple Family Homes - 15 apartments, 936 m^2 heated - 18 apartments, 1099 m^2 heated - 19 apartments, 1151 m^2 heated
5.	BEIS, 2016	N/A	Hybrid	H2	• Converted manufacturer SSHEE data • Average climate
6.	RHPP, 2016	Nov 2011 - Oct 2015 (subset Nov 2013 - Oct 2014)	Standalone	H2	• No intervention to correct usage or installation problems • Only data points with 1.5 < SPF H4 < 4.5 used • Residential properties • Sites all over the UK
7.	EST, 2010	Phase 2: Spring 2011 - Spring 2012	Standalone	H2	• Mostly radiator systems • Designed to produced DHW at 50-55 °C • Sites all over the UK

SPFH1: Core HP components only; SPFH2: Includes supply air fan; SPFH4: Includes immersion heater and pumps

As shown by the N values in Figure 5-3, trials of HHPs to date have been limited in scope in comparison to the trials of standalone heat pumps; results are shown for a small number of installations, rather than across many buildings including a range of housing types. As such, these results do not allow definitive comparisons between standalone and HHP systems. However, the following conclusions can be drawn from the results shown above:

- SPF values for standalone heat pumps vary widely, with field trial results ranging between 1.5 and 3.9, and with a mean value of 2.7. This reflects the potential impact

[19] Sources: 1- Daikin Altherma Hybrid Heat Pump White Paper, 2017; 2- Vaillant trial data extracted from BEIS Domestic Hybrid Heat Pumps report, 2016; 3&4 – Svend Pedersen, DTI report on heat pump field trials, 2015; 5 – SSHEE data extracted from BEIS Domestic Hybrid Heat Pumps report, 2016; 6 - Rowe et al, UCL Energy Institute, 2017. Final report on analysis of heat pump data from the renewable heat premium payment (RHPP) scheme; 7 – EST, 2010. Getting warmer: a field trial of heat pumps.

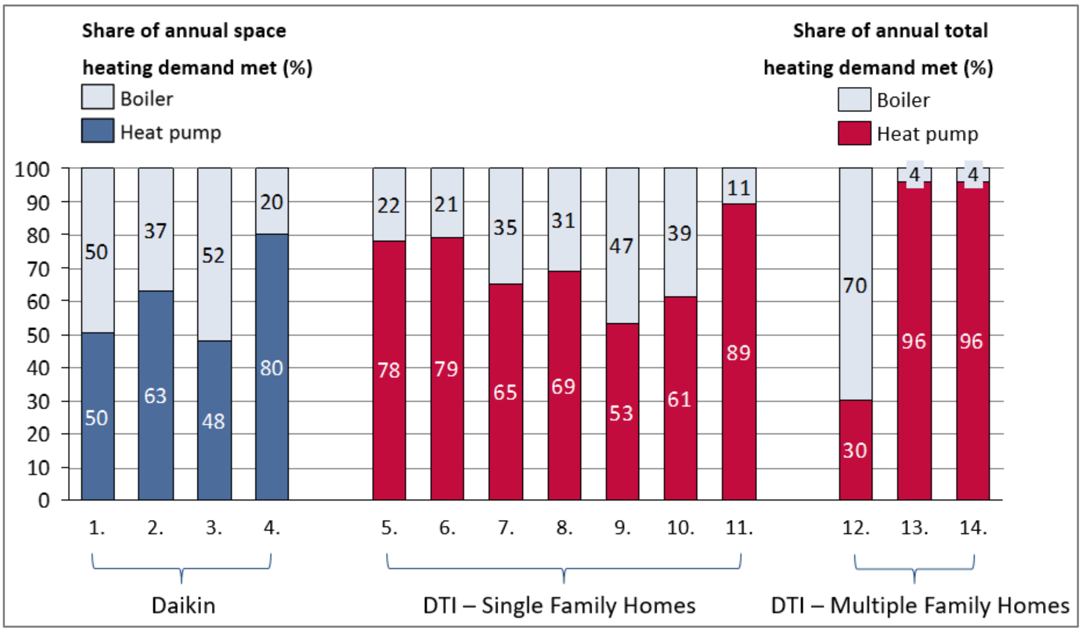
of different building types and operating conditions, and suggests that overall efficiencies can be low if heat pumps are not installed or used in an optimal way.

- SPF values for HHPs can also vary significantly, with field trial results ranging between 2.5 and 4.0, and with a mean value of 3.1 (calculated from individual values). The multiple family home systems tend to have higher SPFs than single family home systems.
- Modelling results suggest that standalone and HHPs both operate more efficiently in buildings with better thermal insulation.

5.1.3 Heating demand met by heat pump

Figure 5-4 shows a selection of field trial results on the share of annual heat demand met by different components of a hybrid system, when installed in various house types with different levels of energy demand. Note that in the multiple family home cases, a HHP system involving a 25 kW heat pump and a 40 kW boiler provided the heat for each cluster of homes.

Figure 5-4 Share of annual heat demand met by heat pump and boiler components of hybrid systems[20]



No.	Source	Monitoring period	Total heat production (HP + Gas boiler) [kWh]	House type
1.	Daikin, 2017	July 2014 - March 2015	11,490	Two bedroom terraced house
2.		April 2014 - March 2015	3,452	Three bedroom semi detached bungalow
3.		May 2014 - March 2015	5,889	Three bedroom semi detached house
4.		May 2014 - March 2015	10,610	Three bedroom semi detached house
5.	DTI, 2015	October 2014 – September 2015	17,716	Single family home
6.			10,502	Single family home
7.			12,062	Single family home
8.			15,206	Single family home
9.			15,687	Single family home
10.			15,823	Single family home
11.			22,773	Single family home
12.			78,430	15 apartments, 936 m^2 heated
13.			91,350	18 apartments, 1099 m^2 heated
14.			88,410	19 apartments, 1151 m^2 heated

[20] Sources: 1- Daikin Altherma Hybrid Heat Pump White Paper, 2017; 2 – Svend Pedersen, DTI report on heat pump field trials, 2015.

The results in Figure 5-4 show that the share of heat met by a heat pump component of a hybrid system can be as low as 30%, or as high as 96%, with various values in between. The percentages shown for the Daikin trial only include space heating, and the hot water demand is met by the boiler, so the overall share met by the heat pump will be lower than the results shown. The variation in the results suggests that house type, which impacts the total heat demand of a building, is likely to be a factor influencing the heat pump share of the annual demand. Interactions between other operating conditions such as the type of emitters, the heating schedule (which may also vary with building type) and the selected control strategy may also have contributed to these differences. For example, if the heat pump is operated in a non-optimal way under a cost-optimised strategy, it will often need to let the boiler take over to ensure that the costs are minimised.

The share of heating demand met by the heat pump will ultimately impact the emissions savings that can be achieved by the system, compared to a gas boiler. However, there is insufficient data available from field trials to determine the likely impacts associated with the full range of different operating conditions. To address this gap in understanding, Chapter 6 and Chapter 7 present the results of technical modelling intended to assess the impacts of various HHP configurations and operating conditions.

5.1.4 Peak demand

The Greater Manchester Smart Energy Project installed and monitored 550 heat pump (HP) and HHP (HHP) systems over some or all of the period from December 2015 to March 2017. The project provides valuable real-world data on the technical performance of 89 domestic HHP systems. The field trial data includes half-hourly metered electricity consumption for the HP and for the household as a whole, along with the half-hourly external temperature. However, the field trial did not capture metered heat output data, or the gas demand of the boiler component of the HHP systems. As such, the field trial data cannot be used reliably to estimate the COP/SPF of the heat pump or HHP system, or the fraction of heat demand met by the HP component versus the gas boiler component.

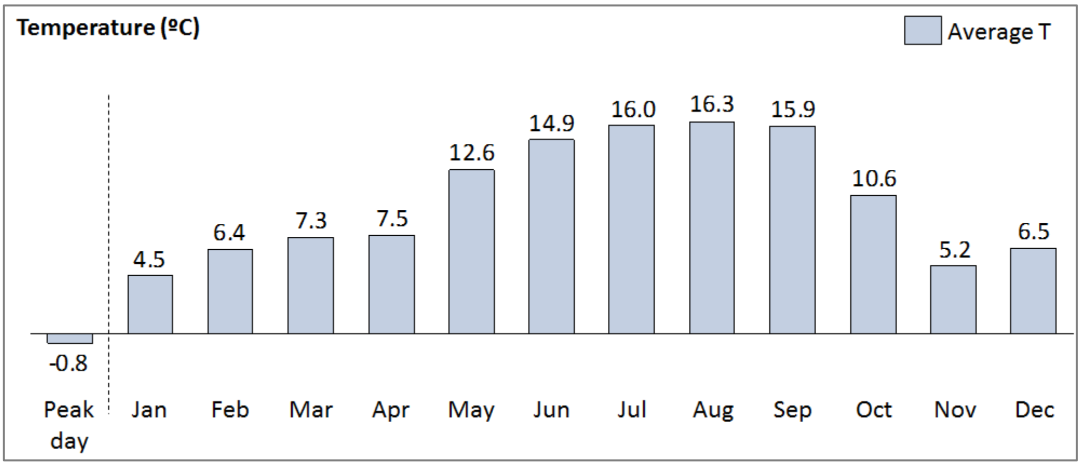
Nonetheless, the data does allow a detailed assessment of the average and peak electricity demand of the HP and HHP systems, and how this varies with external temperature, system size and building type. Here, we summarise the key findings from the field trial relating to the peak electricity demand in HP and HHP systems only. In Sections 6.2 and 6.3, further outcomes of the field trial data are presented, in order to make a detailed comparison with our modelled outputs.

Figure 5-5 shows the average temperatures experienced by the HHPs in the field trial. Figure 5-6 shows the average electricity demand per installation of all HHP systems in the field trial for each month of the year and for the 'peak day' of the year[21]. The results are shown separately for the 5 kW HHP systems and the 8 kW HHP systems (all HHPs were one of these two sizes). The monthly average corresponds to the average electricity demand across all half-hourly periods associated with the month in question (which in some cases may include more than one year), averaged across all relevant installations.

[21] All field trial data presented in this section corresponds to Weekdays, rather than Saturdays or Sundays. Note that it was not possible to remove the specific impacts of DSR interventions which were included as part of the trial. However, the results shown are averages for several different sites (and across a whole month, with the exception of the 'peak day' data), and therefore the DSR interventions (which were applied to different sites at different times) are unlikely to have significantly affected the results. The peak day was defined according to the lowest external temperature rather than the peak in electricity demand in order to avoid spurious 'spikes' in electricity demand (i.e. erroneous or outlying data points) leading to an unsuitable selection of the peak day.

The peak day was defined as the day of the trial with the lowest external temperature period experienced by each installation[22] (which could be a different day according to the period of monitoring for each system).

Figure 5-5 Average temperatures experienced by HHPs in the field trial[23]



The average HHP electricity demand ranges from nearly zero in the summer months to approximately 0.3 kW on the typical day during the winter months. It should be noted that the DHW demand is, according to information accompanying the field trial data, met by the "main system". It is not stated whether the HP component of the HHP contributes to the DHW demand. The non-zero remaining demand in the summer months, of the order 30-50 W, suggests that the HP component does contribute to some of the DHW demand at least in some cases. Little difference is observed for the different system sizes on the typical winter day. On the peak day, the average HHP electricity demand is somewhat higher in the 8 kW case than in the 5 kW case.

Figure 5-6 Average HHP electricity demand for all HHPs in the field trial

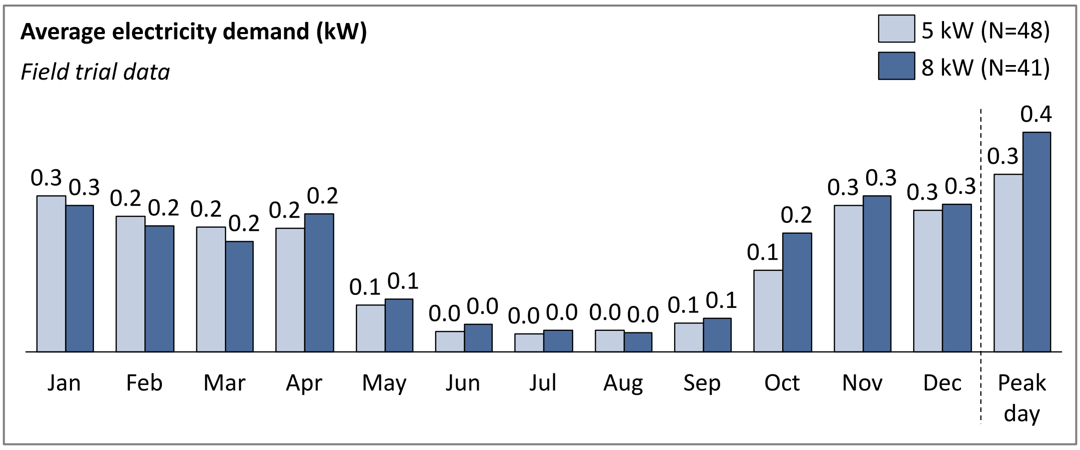


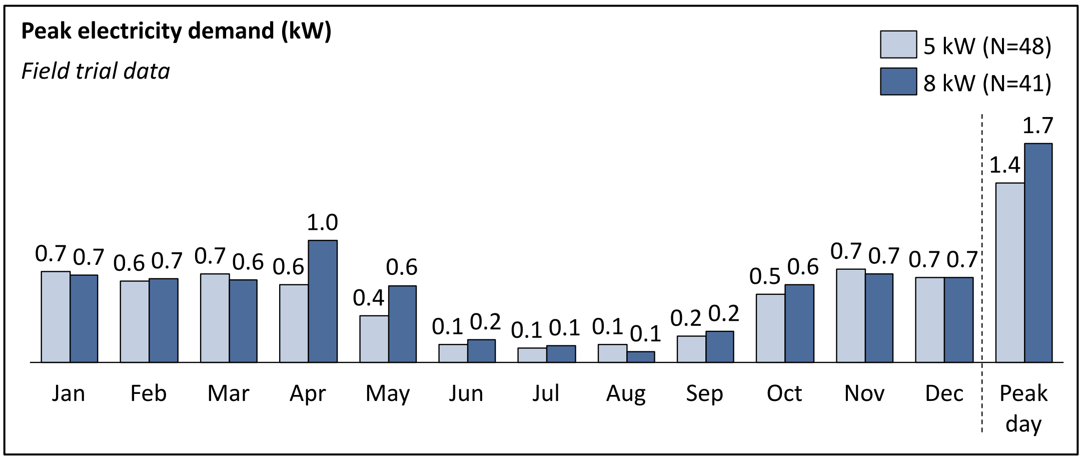
Figure 5-7 shows the peak electricity demand for the same systems, shown for the average day of each month and for the peak day (as defined above). The peak electricity

[22] The peak day was defined according to the lowest external temperature rather than the peak in electricity demand in order to avoid spurious 'spikes' in electricity demand (i.e. erroneous or outlying data points) leading to an unsuitable selection of the peak day.
[23] Note that these temperature are the average values for all HHPs in the field trial – since the HHPs were monitored over different time periods, temperatures experienced by the HHPs on the typical monthly days and on the peak day vary between installations.

demand for each month was derived by averaging the daily demand profile across all days of the month for each relevant installation separately, and then averaging the peak across the relevant installations. Derived in this way, the peak is not diversified across installations – i.e. it is the average of the individual building peaks rather than the peak of the average profile across all buildings. The peak electricity demand for the peak day is, similarly, the average of the peaks determined first separately for each installation, so is also undiversified.

The peak electricity demand ranges from approximately 0.1 kW in the summer months to approximately 0.7 kW on the typical day during the winter months. There is little variation observed across the two system sizes. On the peak day, the peak electricity demand rises to 1.4 kW on average for the 5 kW systems, and to 1.7 kW for the 8 kW systems.[24]

Figure 5-7 Peak HHP electricity demand for all HHPs in the field trial



The results from the HHP field trial therefore suggest that, for the typical winter day, an undiversified peak electricity demand of approximately 0.7 kW per household could be expected. Since the field trial data does not include data on the gas boiler, or heat output data, however, it is not possible to derive the fraction of heat demand met by the HP component, and hence the carbon emissions savings versus the gas boiler counterfactual case. The field trial data also suggests that, on peak days within the trial period – when external temperatures fall to approximately -2 ºC - the peak is substantially higher, of the order 1.4-1.7 kW.

The main advantage of a HHP as compared with a standard HP is, of course, that the peak electricity demand can – in theory – be managed and reduced through the use of the gas boiler. The extent to which this was observed in the field trial is explored next.

Figure 5-8 shows a comparison of the average electricity demand of all 5 kW HHPs in the trial with all 5 kW standard HPs in the trial. The standard HPs have been divided into two groups: (i) HP does not supply DHW and (ii) HP supplies DHW. This is based on data indicating whether the DHW demand is met by the “mains system” (for which the qualitative dataset suggests the HP supplies DHW) or through another method, either using a separate immersion heater or a community hot water system (for which we assume the HP does not supply the DHW).

[24] Note that due to the varying dates of data collection for different sites, additional 8kW sites are included in the sample for Jan-March, compared to the rest of the year, and these sites reduce the group average for the peak electricity demand in those months. This means that April and May values for 8kW sites appear to be outliers.

It can be seen that both the average electricity demand is somewhat lower for the HHPs than for the standard HPs which do not supply DHW, and substantially lower than for the standard HPs which supply DHW. This is the case for all months of the year. Since there is no data on gas boiler operation or heat output, it is not possible to explain this difference with complete certainty, but it suggests that the gas boiler component of the HHP is being used to provide some of the demand both for space heating and DHW across the whole year. This is in keeping with the standard operating mode for the Daikin HHP systems included in the trial, for which the HP component provides heat up to a certain temperature, and the boiler 'tops up' the demand to meet higher levels of demand.

Figure 5-8 Average electricity demand comparing 5 kW HHPs with 5 kW HPs

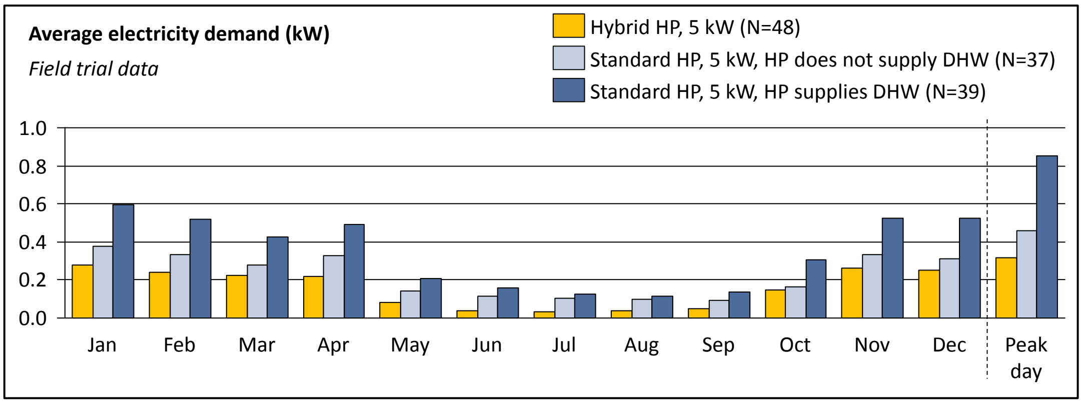


Figure 5-9 shows the peak electricity demand data for the same installations. It can be seen that the peak electricity demand is lower for the HHPs than for the standard HPs, both in the case that the HP supplies DHW and the case that it does not. For the peak day, the peak electricity demand for the HHPs (1.4 kW) is approximately half that of the standard HPs in which the HP supplies DHW (2.7 kW), and around three-quarters of that of the standard HPs in which the HP does not supply DHW (1.9 kW).

Figure 5-9 Peak electricity demand comparing 5 kW HHPs with 5 kW HPs

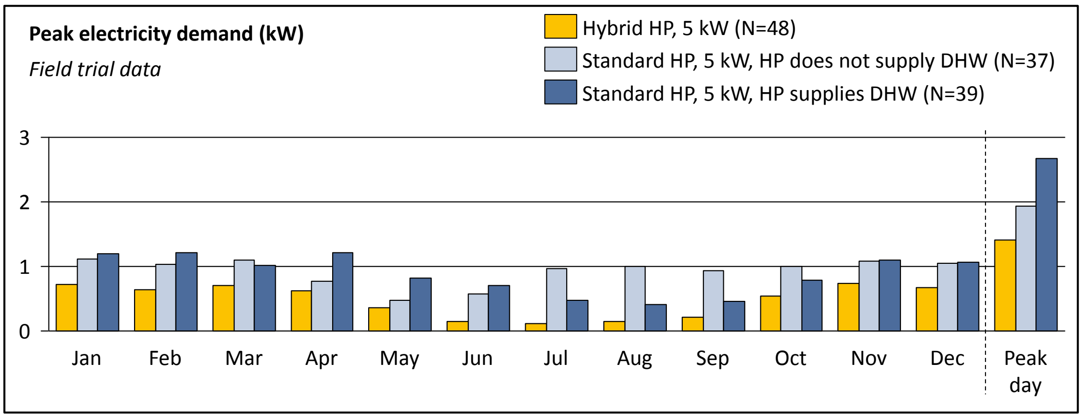
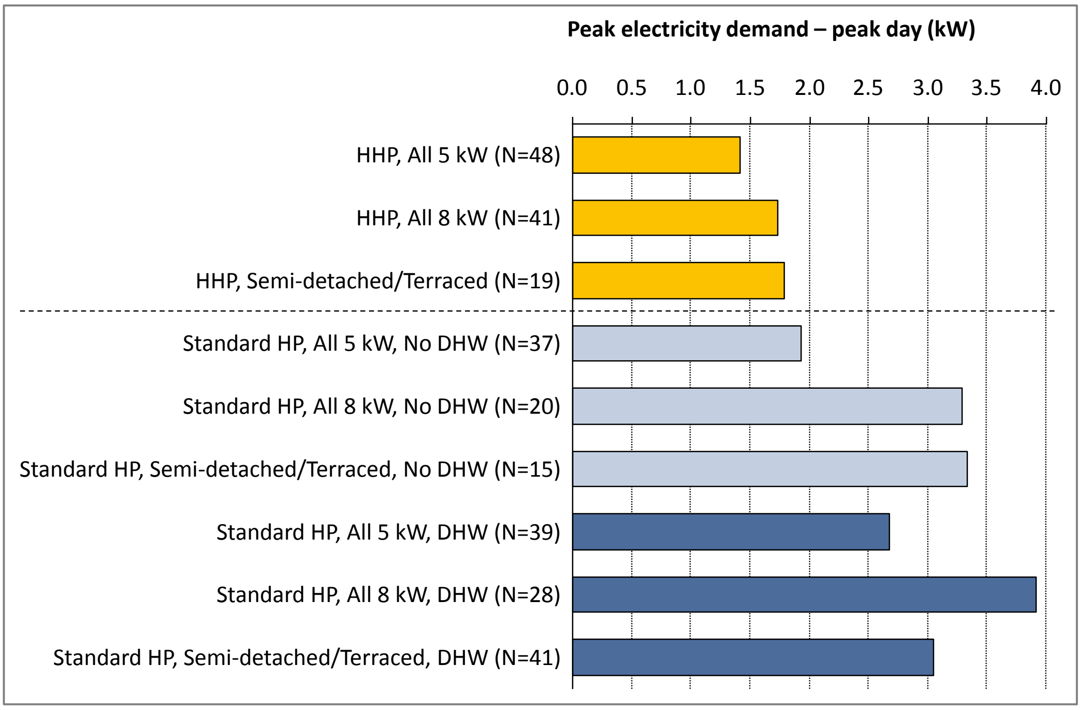


Figure 5-10 presents the peak electricity demand on the peak day for various system types in the field trial. The peak demand is shown separately for 5 kW systems, 8 kW systems and for systems of any size in Semi-detached or Terraced properties. These three groups shown for HHPs, standard HPs where the HP does not supply DHW and standard HPs where the HP supplies DHW. It should be noted that, since the data on building type is very incomplete, as described in the Appendix, the number of data points associated with the Semi-detached/Terraced group is fairly small.

Figure 5-10 Peak electricity demand on the peak day for various system types



The peak electricity demand for the HHP systems ranges from 1.4 kW to 1.8 kW; for the standard HP where the HP does not supply DHW, the peak ranges from 1.9 kW to 3.3 kW; for the standard HP where the HP supplies DHW, the peak ranges from 2.7 kW to 3.9 kW.

At the highest level, therefore, the HHP systems in the field trial succeed in mitigating a substantial proportion of the peak electricity demand associated with similar standard HP systems. However, considering the difference in the average electricity demand in Figure 5-8 it is not clear whether, for the HHP systems in the field trial, the reduction in the peak demand was achieved without a substantial reduction in the share of heating met by the HP component. In the absence of data on gas boiler operation or heat output, it is not possible to establish this.

It is also important to note that, for the HHP systems in the field trial, there was no systematic and sustained incentive to reduce the peak electricity demand on the peak day through, for example, time-of-use tariffs or rebates/rewards for peak reduction. The field trial did include demand-side response (DSR) events, but these were not designed to achieve a systematic reduction in the peak demand on the peak day. It is therefore notable that the peak electricity demand in the standard HP case – which cannot easily be reduced – was found to be as high as 3-4 kW per household in many cases. This is several multiples of the peak electricity demand on the typical January day; it is the potential to mitigate this large additional peak demand for the coldest days that provides much of the motivation for the use of HHPs.

5.2 Potential impact of innovation on domestic HHP performance

A range of potential innovations likely to have an impact on the case for HHPs were identified through the consultation and literature review. These can be categorised along the following lines:

- Innovation in heat pump technology

- Innovation in design and installation
- Innovation in control strategy
- Innovation in thermal storage technology

The potential innovations within each category and the likely impact on HHP performance, cost or user experience are described below.

A table containing aggregated, anonymised comments from stakeholders relating to innovation can be found in the Appendix.

5.2.1 Innovation in heat pump technology

Potential innovations in heat pump technology identified during the consultation and literature review include:

- Improved compressor efficiency (e.g. variable speed)
- High temperature refrigerants
- Reduced costs and aspect ratios

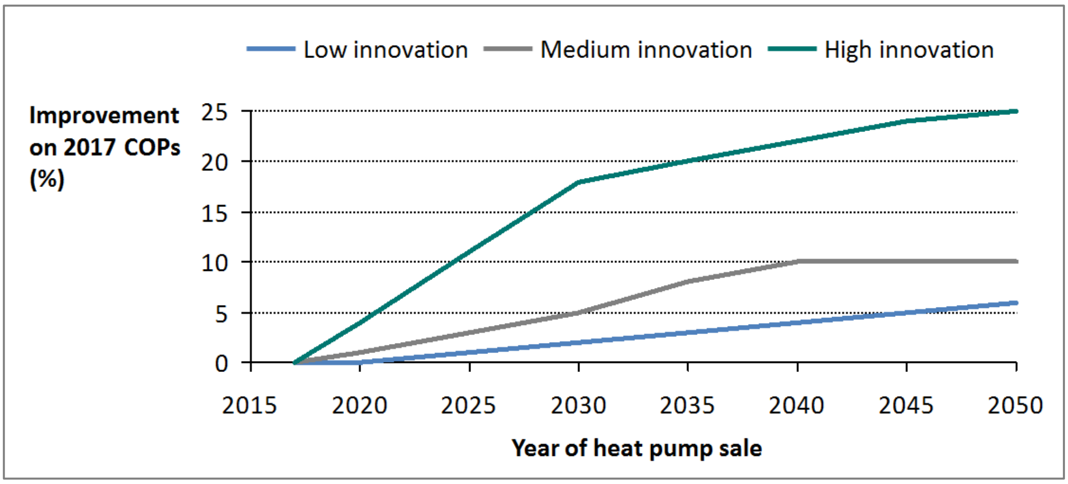
Heat pumps with variable speed compressors or 'inverter driven' technology are currently available from some manufacturers; during the industry consultation, it was suggested that this technology can improve heat pump efficiency by 20% or more; as such, wider implementation could lead to an average overall improvement in heat pump efficiency of around 20%. Further incremental improvements could be possible due to improved heat exchanger efficiency. Such changes would be best described as "implementing best practice", rather than representing true innovations.

Refrigerants such as R32 could allow heat pumps to reach higher output temperatures, and to achieve higher COPs at high output temperatures. According to one stakeholder, R32 could bring COP improvements of 10-15% at 50-55°C as well as enabling HP output temperatures of around 65°C. However, other stakeholders consulted noted that changes to refrigerant legislation would mean that manufacturers would have to 'work harder to maintain efficiencies'. Efficiency improvements at high temperatures would also be possible with refrigerants such as CO_2. However, CO_2-based heat pumps are more costly and also require greater temperature differences than the technologies commonly used for domestic air-source heat pumps; as such, heat pumps e.g. in specific commercial applications are more likely to use this technology before the domestic market.

Several stakeholders took the view that much of the technologically feasible improvements to heat pump efficiency have already taken place in the past decade, and that although incremental improvements (e.g. 2-5% efficiency gains) are possible, efforts should be focused on reducing the costs and aspect ratio of the efficient heat pumps already available.

Given the range and high level of uncertainty around the estimates provided, it is appropriate to consider the potential impacts of heat pump technology innovation on COPs in terms of three scenarios. These scenarios, shown in Figure 5-11, set out the potential improvement in the COP of a new HP over time. It is assumed that the rate of improvement starts to level out by 2040.

Figure 5-11 Scenarios for the impact of innovation on the COPs of heat pumps sold in different years



The potential impacts of these scenarios on overall HHP performance will be presented as part of the technical modelling results, in Chapter 6 (section 6.5).

5.2.2 Innovation in design and installation

The standard of installation for HHPs (and standalone heat pumps) was identified by several stakeholders as an area for improvement and innovation. Appropriate installation of pipework and emitters is required to ensure optimal heat pump performance. In addition, for hybrid systems, the controller must also be set up with appropriate conditions to ensure that the heat pump meets an appropriate share of the heat demand in accordance with its rated capacity.

According to some stakeholders, poor quality installations are decreasing in number, but due to the fact that the domestic heat pump market in the UK is still small, the number of experienced installers is low; if the heat pump market (including the hybrid market) experiences significant growth, the number of qualified installers would need to grow rapidly to meet demand. Particularly for HHPs (where boiler plumbing expertise may be required as well as experience with heat pumps), new approaches to training installers could help to ensure that the overall quality of installations is improved and maintained through the growth in the market.

5.2.3 Innovation in control strategy

The stakeholder consultation revealed a broad consensus within the industry that innovations in heat pump controls could significantly improve the performance of HHPs with respect to cost savings, emissions savings and electricity grid loading. Stakeholders emphasised that for these potential benefits to be realised, the electricity sector (including regulators, retailers and aggregators) would also need to play a role in setting up appropriate market conditions (e.g. domestic time-of-use tariffs linked to electricity loading and/or renewable generation) are in place to facilitate the dynamic optimisation of performance. Several manufacturers were already preparing the release of more advanced controllers, or in conversations with technology providers such as Passiv Systems.

The potential impacts of advanced smart controllers and alternative control strategies (as explored in Chapter 3, section 3.8) are starting to be tested in field trials, including the Greater Manchester Smart Energy Project (a heat pump field trial which includes 89 domestic HHP systems) and the NIA-funded FREEDOM project (a demonstration of 75 ‘smart’ domestic HHPs which will test a range of control strategies with a view to understanding the role that HHPs could play in a demand response market). However, the data currently available does not enable comparisons of performance metrics under specific control strategies. An understanding of the extent of the potential benefits of alternative HHP control strategies could inform the direction of future policy on low carbon heating, and therefore the results of the technical modelling presented in Chapter 6 will include an assessment of HHP performance for different control strategies.

5.2.4 Innovation in thermal storage technology

As discussed in Chapter 3 (section 3.6), thermal storage could have a significant impact on the performance of standalone and HHPs, particularly in terms of improving heat pump performance associated with non-continuous heating profiles and DHW generation. By allowing heat to be generated continuously throughout the day and drawn from storage when required, the use of storage could eliminate peaks in electricity demand and optimise the efficiency of the heat pump.

Storage of this scale is likely to benefit standalone heat pumps to a greater extent than HHPs, in that the inclusion of a boiler in a hybrid system is intended to address the same performance issues as storage would address. However, since there is currently a lack of existing data or literature exploring the impacts of thermal storage on HHP performance, consideration of this will be included in the technical modelling presented in Chapter 6 (section 6.5).

The impact of potential innovation in thermal storage technology will be examined through a hypothetical future scenario where it is feasible to store a significant fraction of the daily space heating demand during the typical winter’s day. At present, this is highly unlikely to be feasible using hot water storage, since the typical daily space heating demand in January is of the order 40 kWh, translating into approximately 1,000 litres of hot water storage. High density thermal storage (such as storage using phase change materials) would bring a reduced storage volume and would be more likely to be feasible in some properties. Current costs of phase change materials would be prohibitive for most dwellings when considered alongside heat pump costs, but ongoing R&D is likely to result in significant cost reductions which could make high density domestic thermal storage more viable in future[25].

[25] Evidence Gathering: Thermal Energy Storage (TES) Technologies, Delta Energy & Environment Ltd. for BEIS, 2016.

6 Modelling the performance of HHPs

This chapter presents the results of technical performance modelling of HHPs for a range of different configurations.

6.1 HHP scenarios

In the following sections, results of the technical modelling will be presented in terms of several key performance parameters, including the peak electricity demand, the share of heat demand met by the heat pump, and the emissions savings compared to a gas boiler counterfactual. The performance of each hybrid configuration will be compared against that of equivalent standalone heat pump counterfactuals.

Table 6-1 summarises the default building type and operating conditions assumed for the purposes of the heat pump and HHP modelling. These default assumptions were defined based on the results of the stakeholder consultation and the literature review, and are intended to reflect the most likely configuration in each case[26].

Table 6-1 Assumptions for default configuration of heat pump systems

Parameter	HHP default case	HP default case
Building type	• Typical semi-detached	• Typical semi-detached
Heat pump size	• 5 kW	• 7 kW
Heating schedule	• Continuous	• Continuous
DHW provision	• Boiler only	• Heat pump
Thermal store (large)	• No thermal store	• No thermal store (small buffer tank for DHW storage only)
Hybrid mode	• Parallel	• N/A
Control strategy	• External T set point	• N/A
Type of emitters	• High T (i.e. no replacement of emitters required)	• Low T (i.e. replacement of emitters required)
Maximum heat pump output temperature	• 55°C	• 55°C

Results will also be considered for the following building types, with heat pump size altered in accordance with the heat demand of the building type:

- Insulated semi-detached
- “Zero carbon” semi-detached new build
- Typical efficiency flat
- Typical efficiency detached
- Large detached

[26] Assumptions on parameters for other building types and scenarios are provided in the Appendix.

Half-hourly heat demand profiles for the different heating schedule options were generated for each building type, calibrated against annual gas demand values as shown in Table 6-2. The assumptions on heating demand for each building type are explained in the Appendix (Section 9.4).

Table 6-2 Key characteristics of the six building archetypes studied

Building type	Thermal efficiency level	Counterfactual heating system	Floor area (m^2)	Annual gas demand for counterfactual (kWh)	
				Space heating	Hot water
Semi-detached	Typical[27]	Gas boiler	95	11,050	1,950
Semi-detached	Insulated	Gas boiler	95	8,850	1,950
Semi-detached	Zero-carbon	Gas boiler	95	4,370	1,950
Purpose-built flat	Typical	Gas boiler	61	5,525	975
Detached	Typical	Gas boiler	135	14,450	2,550
Detached (large)	Typical	Gas boiler	230	24,650	4,350

Results were also considered for a number of variations to the default case. In each of the following HHP cases, one variable was altered compared to the default case, in order to quantify the impact on performance:

- Twice a day heating schedule;
- Smaller capacity heat pump;
- Low temperature emitters;
- DHW provision by heat pump;
- High capacity thermal storage;
- Economic / CO_2 optimisation control strategies.

The last two cases are considered as 'innovation scenarios'. While the other cases could be implemented in 2017, high capacity thermal storage would require significant cost reductions in order to be feasible for installation alongside heat pumps, and optimisation control strategies would rely on some form of hourly or half-hourly time-of-use tariffs for end users, which are not yet in place in the UK.

6.2 Modelled standalone heat pump performance: defining the peak demand problem

In order to assess the performance of hybrid heat pumps in relation to other heating technologies, the performance of these other technologies must be understood. In particular, understanding the various performance metrics of standalone heat pumps and the range of possible outcomes associated with their use is essential in order to draw comparisons and quantify the potential benefits of HHPs.

Heat pumps are most efficient at relatively low output temperatures. Heating schedules which cause significant daily peaks in heat demand will have high flow temperature

[27] I.e. representative of the median level of efficiency in the building stock

requirements, leading to a) lower heat pump efficiencies and b) higher levels of peak electricity demand, compared to heating schedules which have relatively continuous levels of heat demand. As such, **peak electricity demand from heat pumps is strongly dependent on heating schedule.**

"Twice a day" heating schedules lead to two daily peaks in heat demand. Outside of the heating periods, the building cools, and therefore the heating power required to raise the building temperature to the target temperature during the heating periods is high. Heat pumps are not intended to be are used to achieve twice a day heating, and if they are, unless thermal storage is used, the half hourly heat demand during operation can be very high, requiring high flow temperatures at which heat pumps operate inefficiently and may require a resistive heater to "top up" the heat pump output temperatures, leading to high levels of electricity demand.

In addition, the second heating period tends to coincide with the evening peak in national electricity demand. As such, using heat pumps in this way increases the load on local electricity distribution networks at a time when they may already be close to capacity.

However, if heat pumps are used in a continuous heating schedule (as heat pump systems tend to be designed for), the temperature can be maintained throughout the day without significant peaks in heat and electricity demand, as well as enabling high heat pump efficiencies (due to the low flow temperatures required). This maximises the cost and emissions benefits of heat pumps.

Assumptions for heat demand for a "typical" semi-detached house (see Table 6-2 for assumptions) when using a heat pump in a twice a day heating schedule (and the potential impacts on electricity demand) are shown in the Appendix (Section 9.2).

Figure 6-1 shows the "continuous" daily heat demand profile for this type of building on an average January day, a cold January day, and a 1-in-20 year cold January day. The minimum daily temperatures associated with these profiles are shown in the legend.

Figure 6-1 Continuous heat demand profile for a typical semi-detached house on average and peak winter days

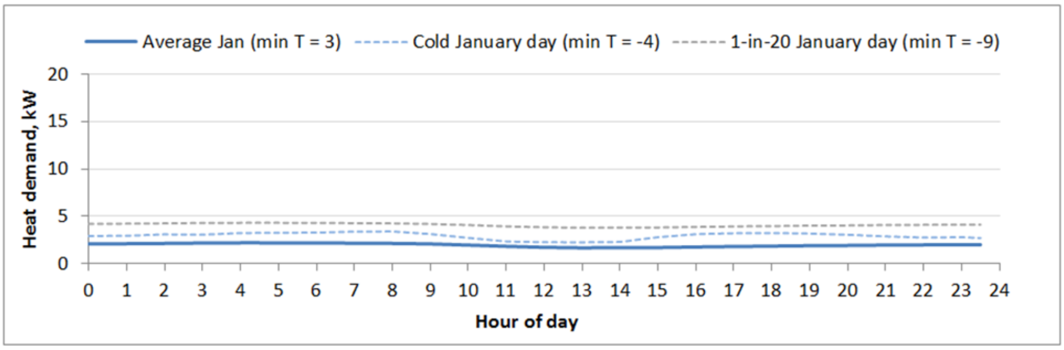
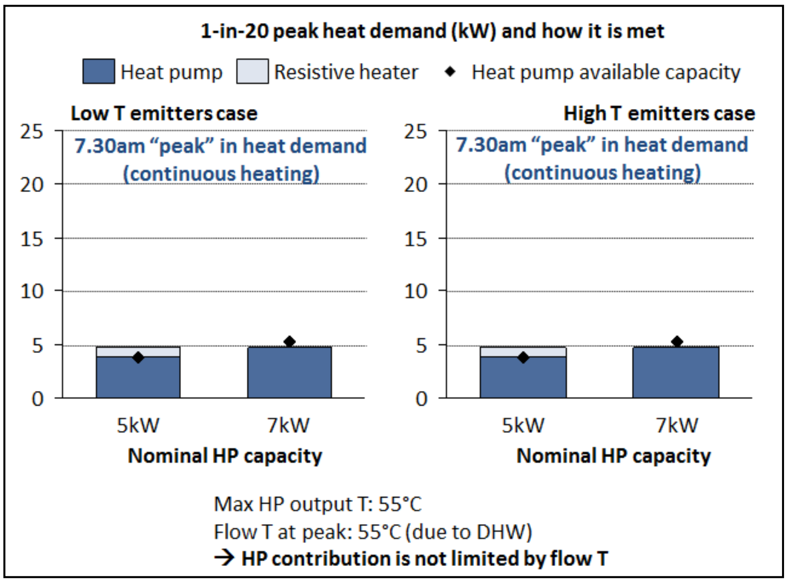


Figure 6-2 shows how the "peak" heat demand in the continuous profile on a 1-in-20 year cold day would be met by a 5kW and a 7kW HP, for typical semi-detached houses with low T or high T emitters.

Note that the total peak heat demand in this profile occurs at 7.30am, and is higher than that suggested in Figure 6-1, due to the additional demand from DHW generation at 45°C. DHW is assumed to be generated throughout the day to fill a DHW store (thus avoiding a higher peak in demand that would come from on-demand DHW generation), alongside generation of hot water for space heating. In the twice a day profile, DHW is generated to fill the store when there is no space heating demand. The demand for DHW also means that the required flow T is automatically set to 45°C (or to the flow temperature required to meet the total heat demand, if this is higher).

Figure 6-2 How peak heat demand in a typical semi-detached house on a 1-in-20 year coldest day is met by heat pumps with various rated capacities (continuous heating)

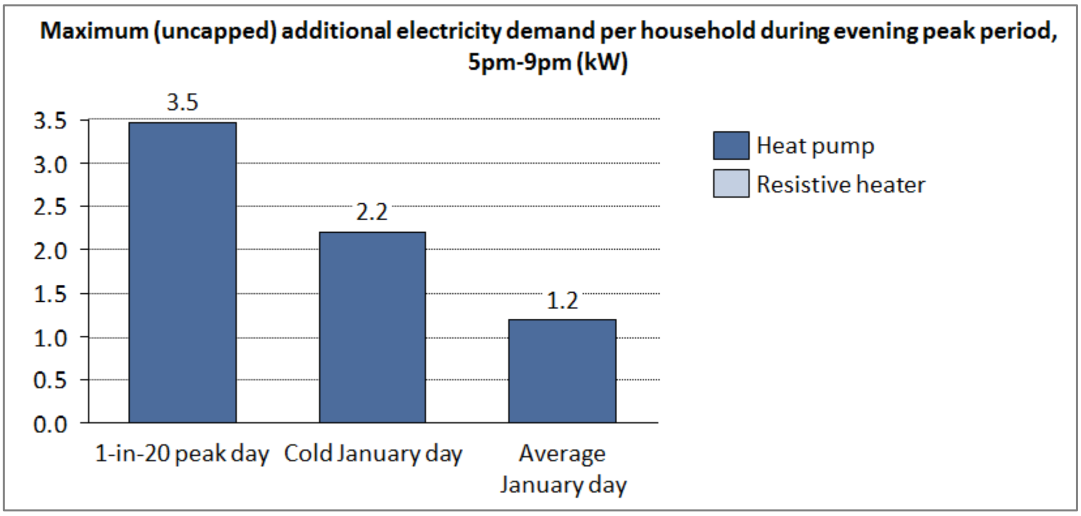


As shown in Figure 6-2, the modelling suggests that with a continuous heating schedule, even at the peak heat demand on the 1-in-20 year cold day, the entire heat demand can be met by a 7kW HP, without requiring the use of a resistive heater. The COP of the 7kW HP at this point would be 1.26 in the Low T emitter case and 1.0 in the High T emitter case (the lower COP for the latter is due to the higher delta T between the flow T and the return T).

Figure 6-3 shows the modelled total electricity demand from the heating system at peak times (i.e. between 5pm and 9pm) in a typical semi-detached house under a continuous heating profile. The results are shown for a 7kW rated HP for a 1-in-20 peak day, the coldest winter day in a typical year, and an average January day.

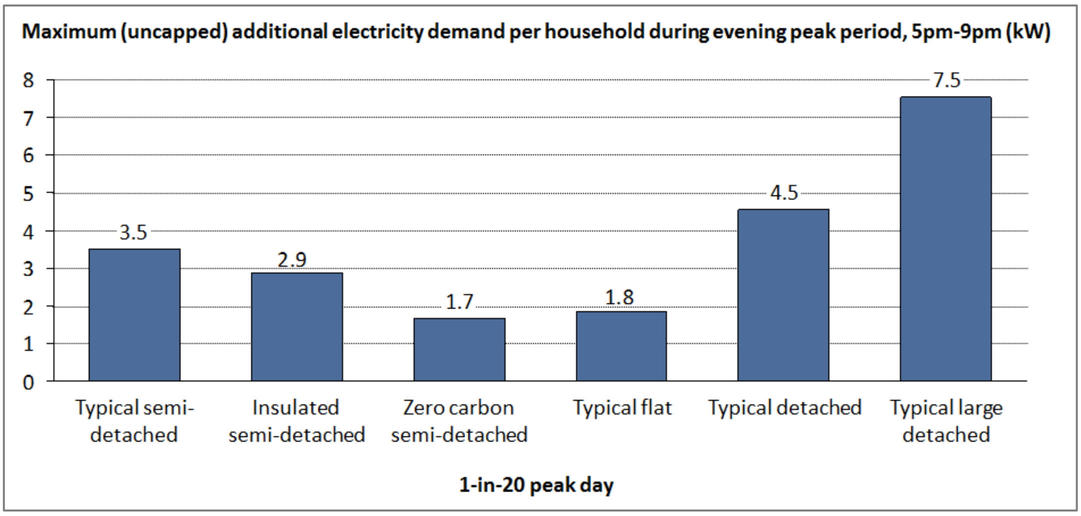
On the 1-in-20 peak day the maximum electricity demand at peak times is 3.5kW, compared to 2.2kW on the coldest winter day and 1.2kW on an "average" January day.

Figure 6-3 Maximum uncapped additional peak electricity demand for a 7kW heat pump following a continuous heating schedule in a typical semi-detached with low T emitters, on a 1-in-20 peak day, a cold January day, and an average January day



In considering the calculated impacts of this modelled continuous heating schedule (shown for a "typical semi-detached" house), it must be emphasised that data collected in HP trials has revealed considerable variation in individual HP electricity demand profiles. Differing user behaviour means that even for houses with similar energy efficiency characteristics, the evening peak electricity demand for a HP on an average winter day could be significantly higher than 1.2kW. In addition to this, the per-household "additional peak demand" varies with the energy efficiency and size of the building; Figure 6-4 shows the modelled results for different building archetypes in the continuous heating schedule.

Figure 6-4 Maximum uncapped additional peak electricity demand on a 1-in-20 year cold day, for heat pumps following a continuous heating profile in various building types, with low T emitters



As shown in Figure 6-4, even with a continuous heating profile, the peak electricity demand from heat pumps could range from 1.7 kW in a new build, zero carbon semi-detached, to 7.5 kW in a large detached house. Heat pump sizing assumptions are based on maximising the share of the heat demand which can be met without using the resistive heater (within the limits of the flow temperature requirements).

6.2.1 Comparing modelling results with HP field trial data

At this point, it is possible to make a comparison between the modelled electricity demand for the standalone HP system and the corresponding observed electricity demand data in the **Manchester-based heat pump field trial**[28]. As described in the Appendix (Section 9.1), the field trial data includes the half-hourly electricity demand for standard HP systems of various sizes in a range of different building types (for a more comprehensive analysis of this dataset, see Section 5.1.4 on p53).

The top graph of Figure 6-5 shows the average electricity demand for the standard HPs in the Manchester field trial, with the data from the 5 kW, 6 kW and 8 kW systems shown separately. The data is presented according to the different HP system sizes rather than by building type because the building type was not specified for the majority (280 of 430) of the installations in the field trial. The average electricity demand on the typical winter days is in the range 0.5 kW to 0.7 kW. On the peak day, the average demand is in the range 0.6 kW to 1.1 kW. These values are comparable to the modelled daily average electricity demand values for the HP in a typical semi-detached house with low T emitters, shown in the bottom half of Figure 6-5: 0.7 kW and 2.1 kW respectively for the continuous heating case. The average external temperatures for the trial and modelled data are quite similar, as shown in Figure 6-5, making the comparison of the results relevant.

Figure 6-5 Daily average electricity demand for Standard HPs by size (field trial) and by heating schedule (modelling results)

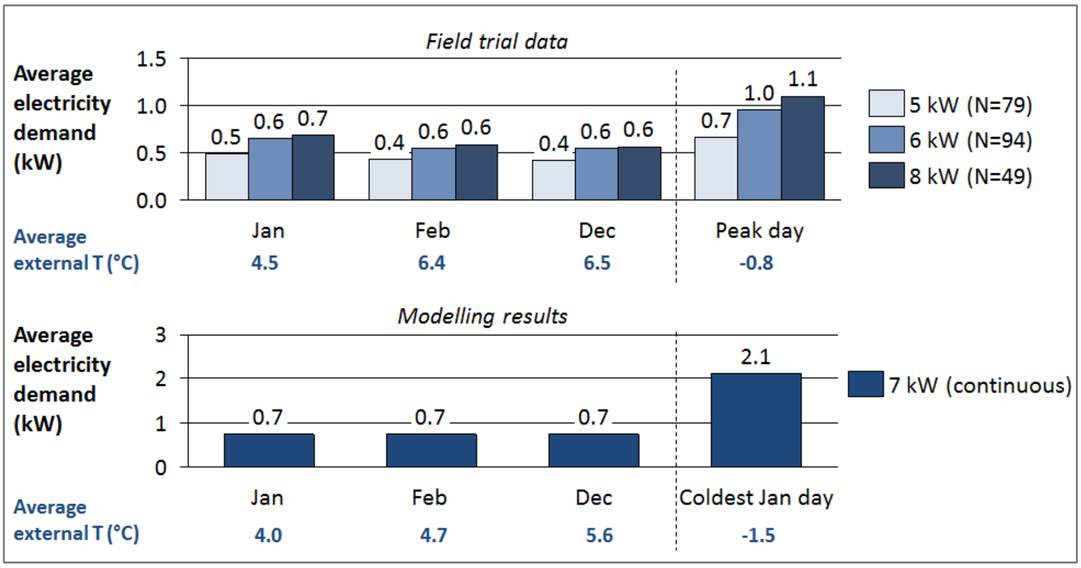
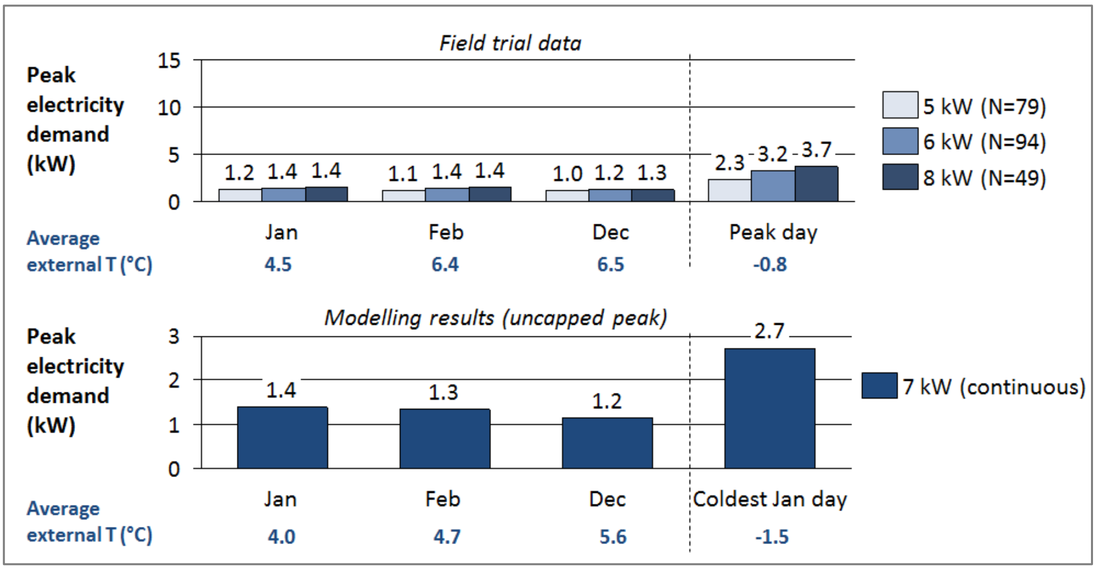


Figure 6-6 shows the peak electricity demand for the same standard HP installations in the field trial, alongside the modelled peak electricity demand for the HP in a typical semi-detached house with low T emitters. The peak electricity demand on the typical winter days is in the range 1.1 kW to 1.5 kW. On the peak day, the peak electricity demand is in the range 2.3 kW to 3.7 kW. The field trial peak demand values are close to the modelled results for the ‘continuous’ heating case.

[28] Since the field trial data does not include metered heat output, it is not possible to compare the modelled heat demand with the field trial data; however, since the field trial data does include HP and HHP electricity demand, it is possible to make a comparison on this metric.

Figure 6-6 Peak electricity demand for Standard HPs by size (field trial) and by heating schedule (modelling results)



Despite the fact that many domestic HPs may follow a relatively continuous heating profile (thus avoiding more extreme peaks in electricity demand which would come from a more "peaky" heating profile), the possibility of significant increases to the evening electricity demand peak resulting from greater uptake of HPs is a cause for concern in relation to the possible cost of upgrading distribution networks to accommodate the additional demand.

By including a boiler that can generate heat alongside or instead of the HP during evening peaks during colder months, HHPs offer the potential to eliminate the risk of significant (or any) increases to the underlying electricity demand at peak times, without incurring a loss in comfort. The next section explores how HHPs could meet domestic heat demand while reducing the peak electricity demand, compared to a heat pump only system.

6.3 Modelled HHP performance: how HHPs can minimise the peak electricity demand

While heat pumps are most efficiently used in a continuous heating profile, and the associated heating systems are designed to be used in this way, user behaviour does not always reflect this.

As such, the ability of HHPs to mitigate high peaks in electricity demand can be illustrated by considering the "worst case" scenario where the system is used in a twice a day heating case (which leads to the highest peaks in the standalone HP case, due to the fact that the heat pump cannot operate at the high flow temperatures required to meet the high heat demand). The assumptions behind the twice a day profile are shown in the Appendix (Section 9.2).

Figure 6-7 shows how a HHP would meet the **peak heat demand** on average and peak days across the year, in switch mode and parallel operating modes, on a twice a day heating schedule. The configurations represented here are assumed to include a 5kW heat pump and a combination boiler (which always meets the DHW demand and also meets the space heating when it cannot be met by the heat pump). An external temperature set-point of -7 is also assumed (i.e. the boiler automatically takes over when the outside air drops below this temperature), and the house is assumed to have high temperature emitters.

Figure 6-7 HHP meeting peak heat demand on average and peak days (twice a day heating, boiler always provides DHW, high T emitters)

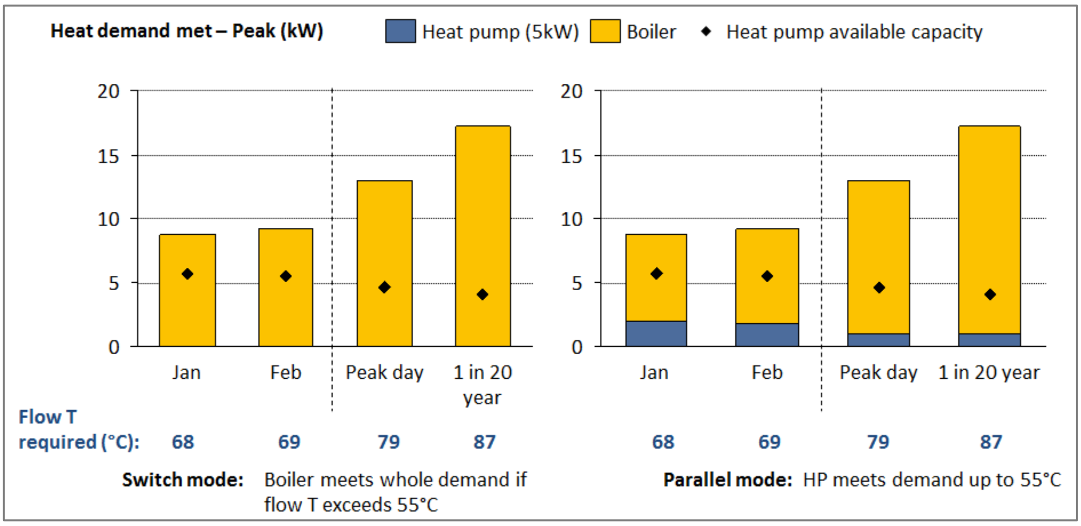


Figure 6-7 shows that in the hybrid configuration, when the heat pump cannot work at the required flow temperatures or has insufficient capacity to meet the demand, the boiler meets the whole demand (in the switch case) or meets the remainder of the demand (in the parallel case). This means that at the time of peak heat demand the electricity demand is significantly reduced (to zero in the switch case, where the boiler meets the whole demand). Figure 6-8 shows the **electricity demand** at the time of peak heat demand for the parallel mode, showing that with a HHP, the peaks in heat demand associated with the twice a day heating schedule do not lead to very high levels of electricity demand at these times.

Figure 6-8 Electricity demand at time of peak heat demand for average and peak days (HHP, twice a day heating, 5kW HP, parallel mode, boiler always provides DHW, high T emitters)

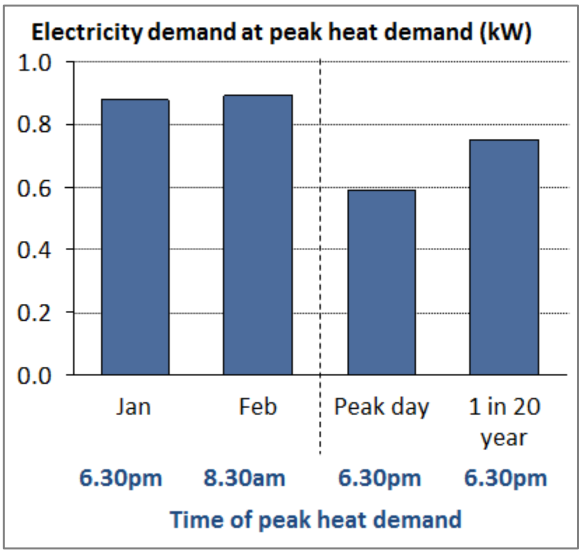


Figure 6-9 shows the modelled peak electricity demand during the evening period on an average January day and on a 1-in-20 year cold day, for HHPs in the two operating modes (assuming a 5kW HP component, high T emitters in a semi-detached house, and a set-point of -7°C). The equivalent peak electricity demand is also shown for a HHP following a continuous heating profile (other assumptions are the same as the twice a day case). Note that the peak electricity demand will not necessarily be exactly the same as the electricity demand at the time of peak heat demand (which also includes demand for DHW, which is met by the boiler).

Figure 6-9 Maximum uncapped additional peak electricity demand for different HHP operating modes and heating schedules in a typical semi-detached (twice a day heating, 5kW HP, boiler always provides DHW, high T emitters)

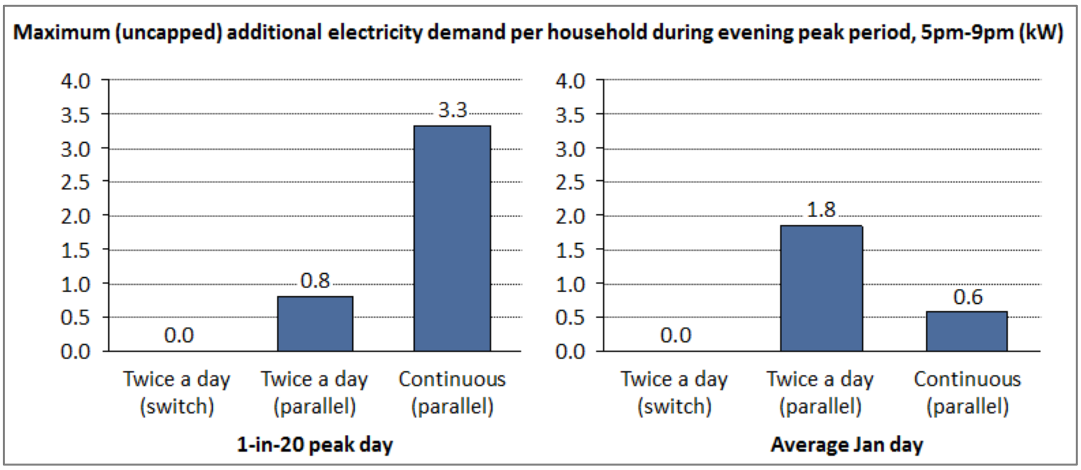
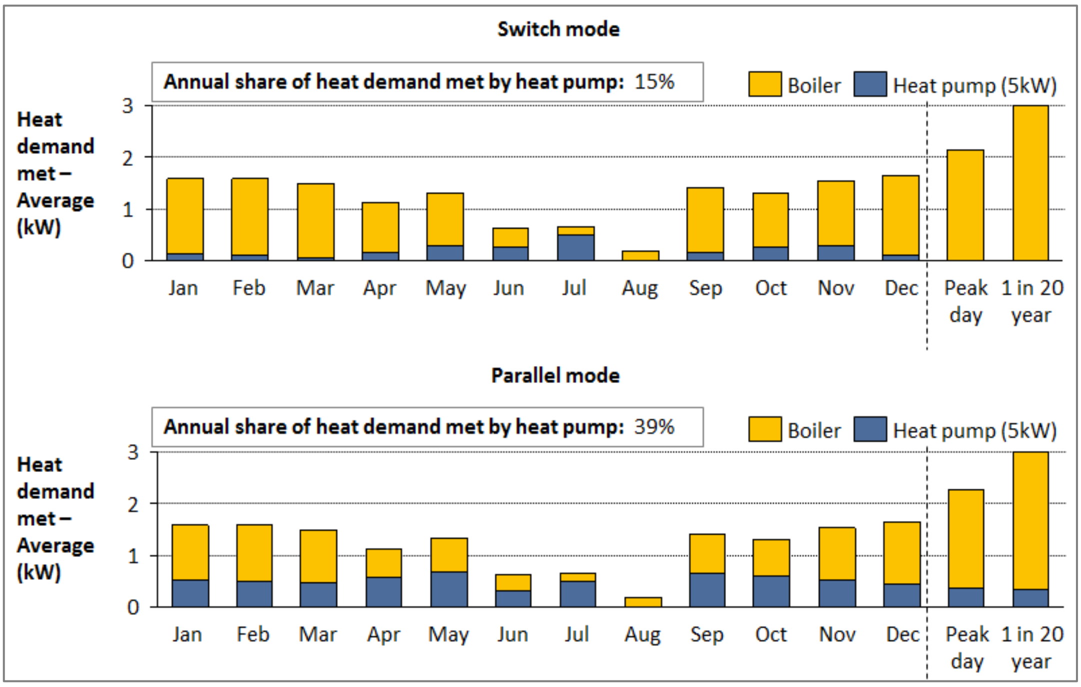


Figure 6-9 shows that the peak electricity demand in the evening period can be strongly dependent on heating schedule and operating mode. Using switch operation in a twice a day heating schedule effectively ensures that the heat pump is not used to meet the evening heat demand on cold days, and therefore avoids any additional electricity demand. The other results are slightly counterintuitive. For example, for the twice a day schedule, the peak electricity demand in the parallel mode on the average January day (1.8kW) is higher than that on the peak day (0.8kW). This is because the heat pump can contribute more to the heat demand on the average day, due to the lower flow T requirements associated with the lower heat demand. Similarly, the peak electricity demand in the continuous case for the peak day (3.3kW) is higher than the twice a day case, because the overall demand is lower and therefore the HP component can meet the whole demand.

Comparing the peak electricity demand values shown in Figure 6-9 to those shown for standalone HPs in Figure 6-4, it is clear that a HHP can limit the maximum additional load on the grid per household, even in the case of a twice a day heating schedule (which would cause much greater increases in electricity demand if used with a standalone HP – shown in Appendix Section 9.2). Furthermore, in the hybrid case different control strategies could be employed which would reduce the peak further; the presence of the boiler provides the option to turn off the heat pump at times of high demand (e.g. in response to a signal from the grid). This is a fundamental advantage of HHPs over standalone heat pumps, with respect to managing electricity grid loading.

However, HHPs reduce the peak electricity demand by using the boiler to meet high levels of heat demand, and the extent to which this occurs in the twice day heating case means that the fraction of heat demand met by the heat pump over the course of the year is low. Figure 6-10 shows how the average heat demand would be met for average and peak days across the year by a HHP running on a twice a day schedule in switch and parallel modes, in a typical semi-detached with high T emitters. The overall annual share of heat demand met by the heat pump is also shown.

Figure 6-10 HHP (5kW heat pump) meeting average heat demand on average days (twice a day heating, boiler always provides DHW, high T emitters)



The low share of annual heat demand met by the heat pump in the twice a day heating schedule, (15% in switch mode and 39% in parallel mode) means that the overall potential for emissions reductions associated with using the heat pump is low (as are any potential fuel cost savings). This emphasises the fact that a twice a day heating schedule is not the optimal way to use heat pumps (it should be noted, however, that in both of these cases, the boiler is assumed to meet 100% of the DHW demand, which accounts for 15% of the total annual heat demand. If the HP component could contribute to meeting the DHW demand, this could increase the total share met by the HP – see Section 6.4).

If a continuous heating schedule is employed, the heat pump component of HHPs can meet a higher share of the heat demand, whilst still achieving reductions to peak electricity demand compared to the standalone HP case. In a continuous mode, the heat demand is spread throughout the day and therefore the output temperature of the heat pump is less likely to be a limiting factor. As such, if the HP is sufficiently sized, it could theoretically meet the majority of the heat demand throughout the year, within operating boundaries such as external temperature and any economic constraints.

Figure 6-11 shows how the peak heat demand for a continuous heating schedule could be met on an average January day and on a 1 in 20 year cold day, by HHPs with different sized HPs, in switch and parallel operating modes. The modelling for these results assumes that the DHW demand is met on demand by the HP, where possible, in order to demonstrate the theoretical limits of different systems in meeting heat demand.

Figure 6-11 Peak heat demand from HHPs with different sized HP components on an average January day and on a 1-in-20 year cold day (typical semi-detached, continuous heating, high T emitters, heat pump provides DHW where possible, no DHW storage)

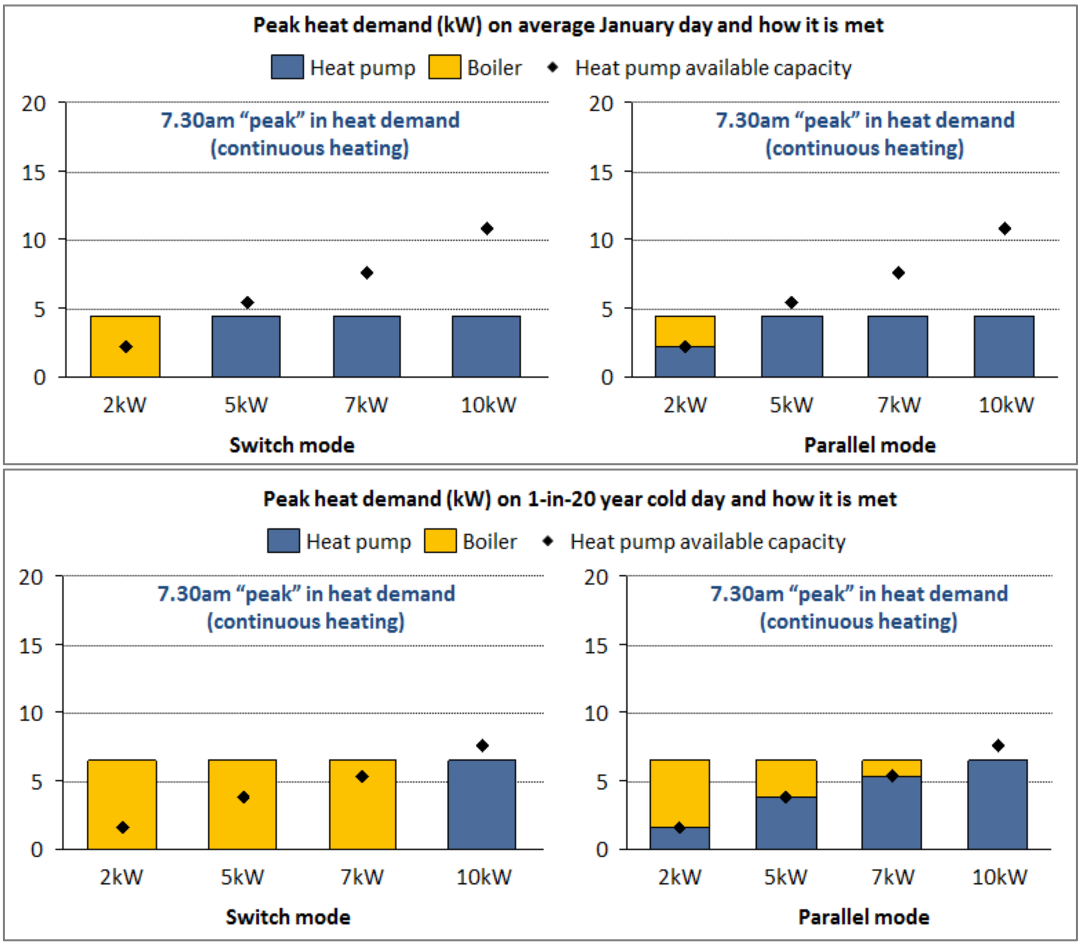


Figure 6-11 shows that for a continuous profile, under a parallel operating mode, a 5kW heat pump would be capable of meeting all but the extreme cases of peak heat demand for a typical semi-detached with a high T heating system, even when this includes DHW, which is assumed to be generated on demand at 45 degrees C[29]. The switch mode, on the other hand, would only allow the heat pump to operate when it can meet the whole demand, and as such the HP would meet a lesser share of the peak and of the total demand, compared to the parallel case.

The preceding figures have shown that heat pump size, heating schedule and operating mode can have significant impacts on the overall performance of HHPs. If appropriate sizing, operating modes and control strategies are employed, HHPs have the potential to meet a high share of overall heat demand with the HP (and thus high emissions savings compared to a gas boiler) whilst also reducing the peak electricity demand compared to standalone HPs (particularly during the evening peak of domestic electricity demand). The following section considers the impacts of various HHP configurations in terms of

[29] In this case, the peak electricity demand would be higher that of the standalone HP operating in a continuous mode (due to the lower efficiency when operating with high T emitters).

electricity demand and emissions, to identify which configurations are most likely to maximise the benefits of HHPs.

6.4 Impacts of different HHP configurations

Table 6-3 summarises the parameters for a range of different HHP configurations, including the default continuous heating case, for different housing types. The key impacts (peak electricity demand, share of heating met by heat pump, and CO_2 emissions savings relative to a gas boiler counterfactual) are considered for each case. Note that the base case uses a continuous heating strategy and the parallel mode of hybrid operation.

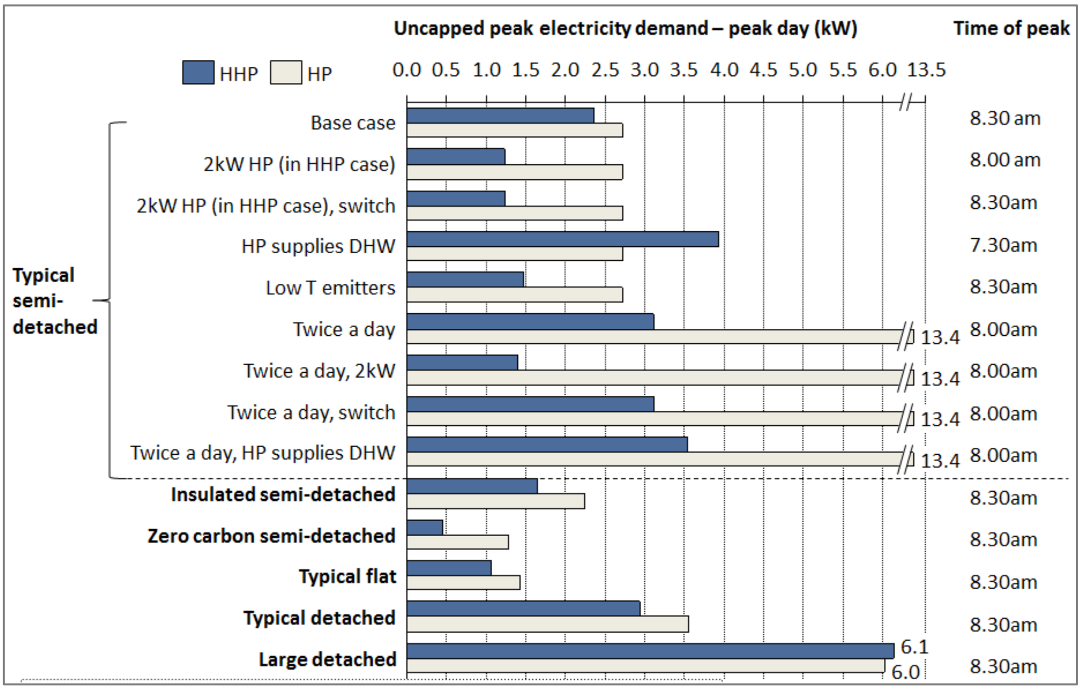
Table 6-3 Summary of different HHP configurations tested in modelling (differences compared to base case are underlined for each scenario)

Scenario name	Building type	HP size (in HHP case)	Heating schedule	Hybrid mode	DHW provision	Type of emitters
Base case	Typical semi-detached	5kW	Continuous	Parallel	Boiler	High T
2kW HP	Typical semi-detached	2kW	Continuous	Parallel	Boiler	High T
2kW HP, switch	Typical semi-detached	2kW	Continuous	Switch	Boiler	High T
HP supplies DHW	Typical semi-detached	5kW	Continuous	Parallel	HP	High T
Low T emitters	Typical semi-detached	5kW	Continuous	Parallel	Boiler	Low T
Twice a day	Typical semi-detached	5kW	Twice a day	Parallel	Boiler	High T
Twice a day, 2kW	Typical semi-detached	2kW	Twice a day	Parallel	Boiler	High T
Twice a day, switch	Typical semi-detached	5kW	Twice a day	Switch	Boiler	High T
Twice a day, HP supplies DHW	Typical semi-detached	5kW	Twice a day	Parallel	HP	High T
Insulated semi-detached	Insulated semi-detached	5kW	Continuous	Parallel	Boiler	High T
Zero carbon semi-detached	“Zero carbon” new build semi-detached	3kW	Continuous	Parallel	Boiler	High T
Typical flat	Typical flat	3kW	Continuous	Parallel	Boiler	High T

Typical detached	Typical detached	8kW	Continuous	Parallel	Boiler	High T
Large detached	Large detached	12kW	Continuous	Parallel	Boiler	High T

Figure 6-12 shows the (uncapped) peak electricity demand on the coldest day in a typical year, for each HHP and standalone heat pump configuration. For the typical semi-detached building (that is, for all cases above the dotted line in the figure), for the HHP case, the peak electricity demand on the peak day ranges from 0 kW for the twice a day, 2kW, switch HP case, to 3.94 kW for the HP supplies DHW case. With the exception of the HP supplies DHW case, the peak demand is always lower in the HHP case than in the equivalent HP case.

Figure 6-12 Uncapped peak electricity demand from HHPs and standalone heat pumps on coldest (peak) day of a typical year (assumes electric resistive backup in the standalone HP case)



The modelled peak electricity demand for the various HHP configurations can be compared with the peak electricity demand observed for HHPs in the Manchester field trial. Figure 6-13 shows the peak electricity demand derived for all HHP installations in the field trial, presented separately for all 5 kW systems, all 8 kW systems (all HHP installations were one of these two sizes) and all systems in semi-detached/terraced houses. Since the building type information is unavailable for the majority of installations, the number of confirmed semi-detached/terraced installations is small, but they are shown as a useful comparison with the modelled semi-detached case. Information accompanying the field trial data suggests that the DHW demand is met, in all HHP cases, by the gas boiler. There is no information on the type of emitters installed.

For the field trial HHP installations, the peak electricity demand on the peak day (minimum temperature -0.8, vs. -1.5 for the modelled peak day) is 1.4 kW for the 5 kW systems and 1.7 kW for the 8 kW systems. For the subset known to be installed in semi-detached or terraced houses, the peak electricity demand on the peak day is 1.8 kW. These values are seen to be comparable with the modelled values, and are at the lower end of the modelled range shown in Figure 6-12.

Figure 6-13 Peak electricity demand for HHPs in the Manchester field trial

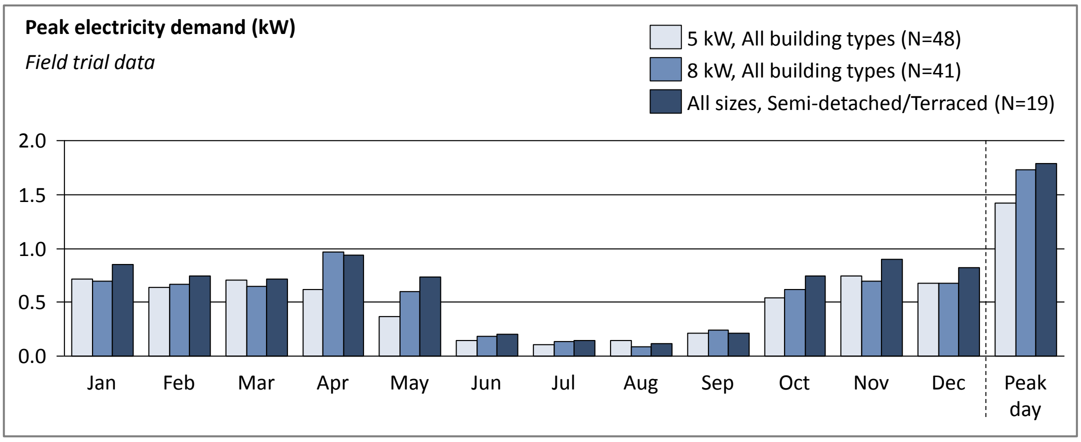
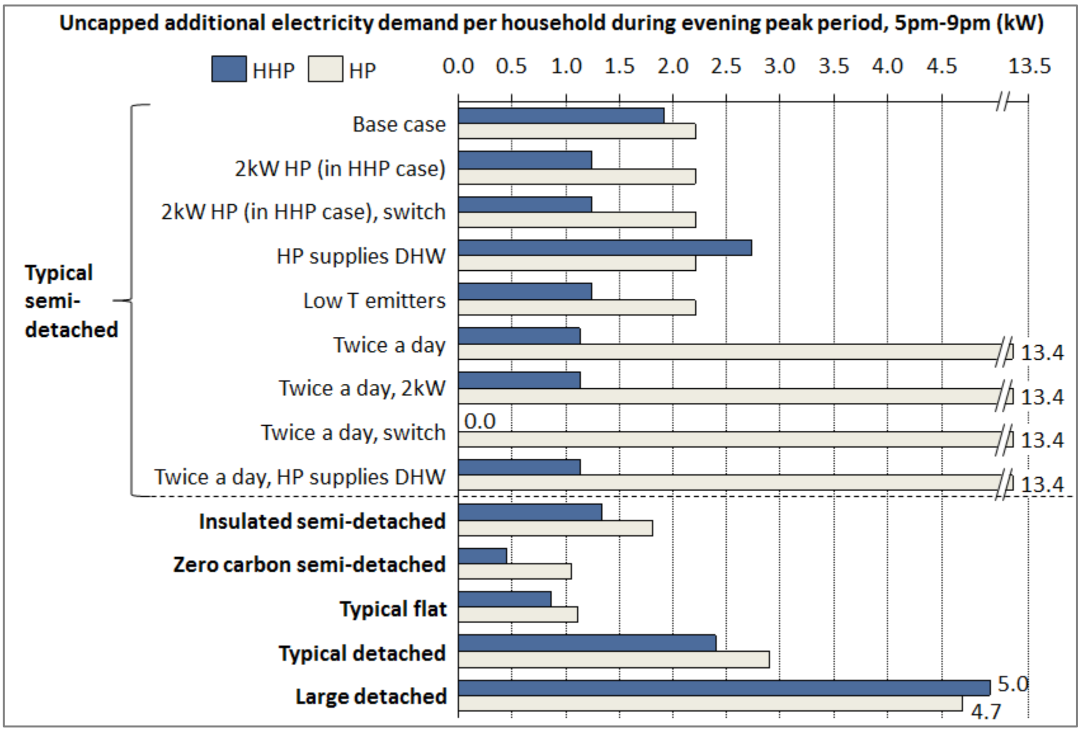


Figure 6-14 shows the (uncapped) peak electricity demand during the evening peak demand period on the coldest day in a typical year, for each HHP and standalone heat pump configuration. For the typical semi-detached building, in the HHP case the peak electricity demand on the peak day ranges from 0 kW for the twice a day, 2kW, switch case, to 2.74 kW for the HP supplies DHW case.

Figure 6-14 Uncapped evening peak electricity demand from HHPs and standalone heat pumps on coldest (peak) day of a typical year. Assumes electric resistive backup in the standalone HP case – note that standalone HPs are not designed to be used with a twice a day heating schedule.



The results shown in Figure 6-14 indicate that the HHP parameters that bring a reduction in the additional electricity demand at peak times, compared to the base case for a typical semi-detached house (and relative to the standalone heat pump case) are: a) using a smaller heat pump, b) using low temperature emitters, and c) following a twice a day use case rather than a continuous heating schedule.

Using a smaller heat pump within a hybrid configuration causes the capacity of the heat pump to become a limiting factor, and as such this inherently limits the electricity demand of the system.

Using low temperature emitters instead of high temperature emitters can also reduce the peak electricity demand, due to the fact that heat pumps operate more efficiently at lower temperatures, and therefore for a given heat demand, the electricity demand from the heat pump will be lower.[30] Note that the standalone heat pump is assumed to use low temperature emitters in all cases, whereas the default setting for HHPs in the modelling is to use standard or 'high temperature' emitters.

The reduced peak demand in the twice a day case is a result of the high required flow temperature under the twice a day profile, and the temperature limit of the heat pump, which effectively limits the useful heat that can be provided by the HP (as discussed above – see Figure 6-7).

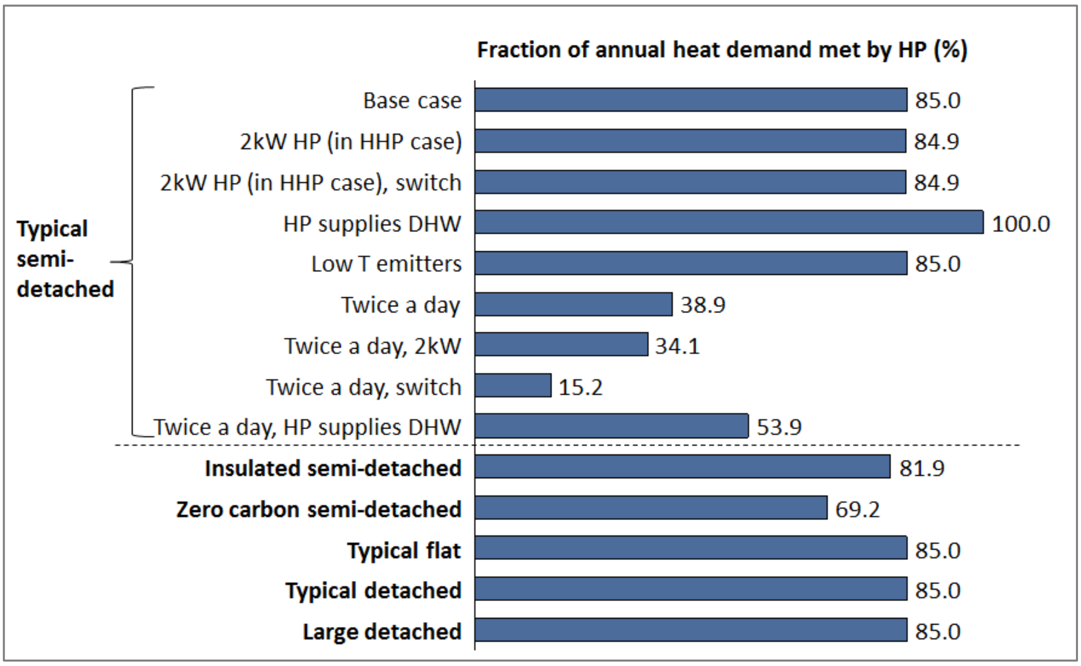
According to the results shown in Figure 6-14, using a switch mode instead of a parallel mode does not have a significant impact on the evening peak electricity demand unless the HP is also being used in a twice a day mode, in which case this will lead to a further reduction to the peak (as a result of the heat pump being unable to partially meet the heat demand).

In addition to these configurations, in a HHP system various control strategies could be used that fundamentally limit the conditions at which the heat pump works, thereby reducing the peak electricity demand. This could be as simple as adjusting the temperature set-point so that at times of peak demand (i.e. on colder days) so that the heat pump allows the boiler to take over. In addition, smart controllers could potentially enable the heat pump to switch off (or turn down, in a parallel hybrid mode) in response to grid signals at times of peak network loading, or in response to dynamic pricing. This capability is one of the main policy motivations for considering HHPs as an alternative to standalone heat pumps.

Figure 6-15 shows the overall annual share of heating met by the heat pump (based on average days), for various HHP configurations. With the exception of the twice a day heating profile cases, in all cases shown the heat pump can meet virtually the entire space heating demand, with the remaining 15%-30% of annual heat demand coming from DHW demand, which is met by the boiler.

[30] 'High temperature emitters' are designed for operation at 80/60 flow and return temperatures, whereas 'low temperature emitters' are assumed to be designed for operation at 40/30 flow and return temperatures.

Figure 6-15 Share of annual heat demand met by heat pump for different HHP configurations (based on average days for each month)



The modelled results for the 2kW HP cases suggest that the smaller heat pump can meet almost as much of the space heating demand as the 5kW HP. However, it should be noted that the annual results shown here are based on repeating the 'average' days for each month. In reality, heat demand could be slightly more 'peaky' on some days than is represented the modelled 'average' heat demand profiles. If the peak space heating demand exceeds the heat pump capacity, this could have the effect of reducing the overall share of demand met by the smaller heat pump.

When the 2kW HP is being used in a twice a day mode, using a switch mode instead of a parallel mode further reduces the share of demand met by the HP (as a result of the heat pump being unable to partially meet the heat demand).

Figure 6-16 shows the CO_2 emissions savings for systems installed in 2017 relative to a gas boiler counterfactual, for various hybrid and standalone heat pump configurations.

Electricity carbon intensity was based on the current UK grid generation mix, calculated on a half hourly basis. Each half hourly value accounts for daily and seasonal variations in the generation mix, on the basis of Elexon data for 2016 and 2017, combined with emissions factors for the individual generation technologies.

Figure 6-16 Emissions savings of hybrid and standalone heat pump systems relative to a gas boiler (based on electricity carbon intensity in 2017). Note that standalone HPs are not designed to be used with a twice a day heating schedule.

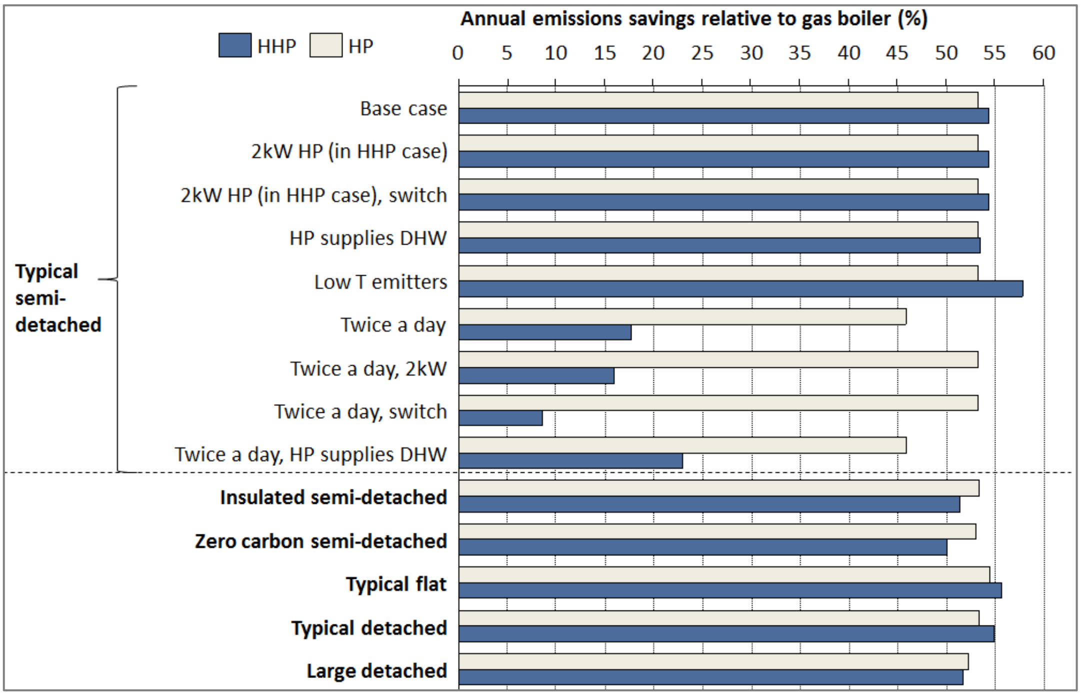
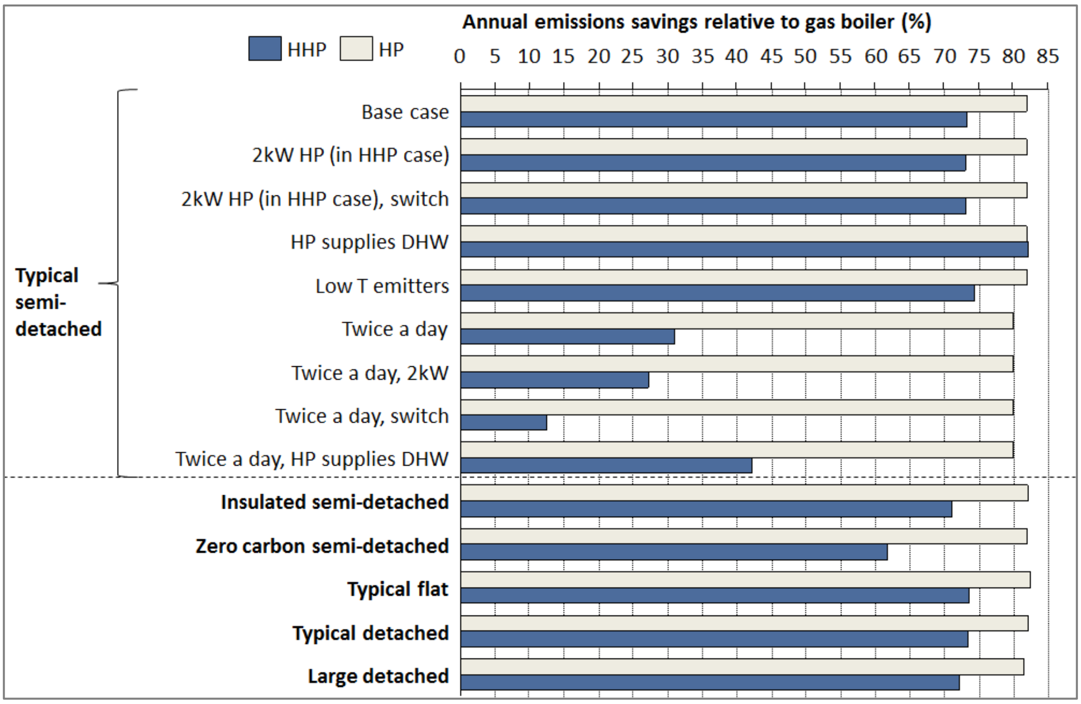


Figure 6-16 shows that, with continuous heating profiles, the emissions savings compared to a boiler are similar for heat pumps and HHPs; around 50% or more for all the continuous heating cases. In the low T emitters case, where the HHP system benefits from efficiency gains due to operating at low temperatures (which is the default case for the heat pump), the hybrid case brings around 5% additional savings over the heat pump case. This suggests that when the standalone heat pump system is operating at low efficiencies (i.e. at peak demand or to meet DHW demand), it is more carbon intensive than using the gas boiler.

In the twice a day heating cases, the emissions savings from HPs are significantly lower than for the continuous heating cases, due to the lower efficiency of meeting a twice a day heating profile. More significantly, the hybrid cases have much lower emissions savings than the standalone heat pump equivalent, due to the share of demand met by the boiler.

Figure 6-17 shows the equivalent emissions savings for the same systems, but using the annual average projected emissions intensity for UK electricity in 2030, which is significantly lower than in 2017, in line with decarbonisation targets (note that annual average values are used as opposed to half hourly values).

Figure 6-17 Emissions savings of hybrid and standalone heat pump systems relative to a gas boiler (based on projected electricity carbon intensity in 2030). Note that standalone HPs are not designed to be used with a twice a day heating schedule.



The results presented in Figure 6-17 show that in 2030 (with reduced electricity carbon intensity compared to 2017) the emissions savings achieved by HHPs following continuous heating schedules are significantly below those achieved by standalone heat pumps. The percentage differential with continuous heating is highest for the case of the 'zero carbon' new build, which has the lowest heat demand. For the twice a day heating cases, the HHP achieves a maximum of 42% reduction in emissions compared to the gas boiler if the HP supplies DHW and up to 31% if DHW is provided by the boiler, whereas the standalone heat pump could achieve an 80% reduction (although, as has been discussed, using a heat pump on a twice a day profile will result in very high peaks in electricity demand as well as losses in comfort when the electricity demand exceeds the domestic power limit). However, in all other cases the HHP still achieves at least a 60% emissions reduction compared to the gas boiler.

In summary, the modelling results so far suggest that HHPs have the potential to reduce the additional load on the electricity grid, compared to heat pumps, without drastically reducing the emissions benefits of heat pumps. However, HHPs should follow a continuous heating profile if the emissions benefits are to be maintained at similar levels to those of standalone HPs.

6.5 Impacts of innovation on heat pump and HHP performance

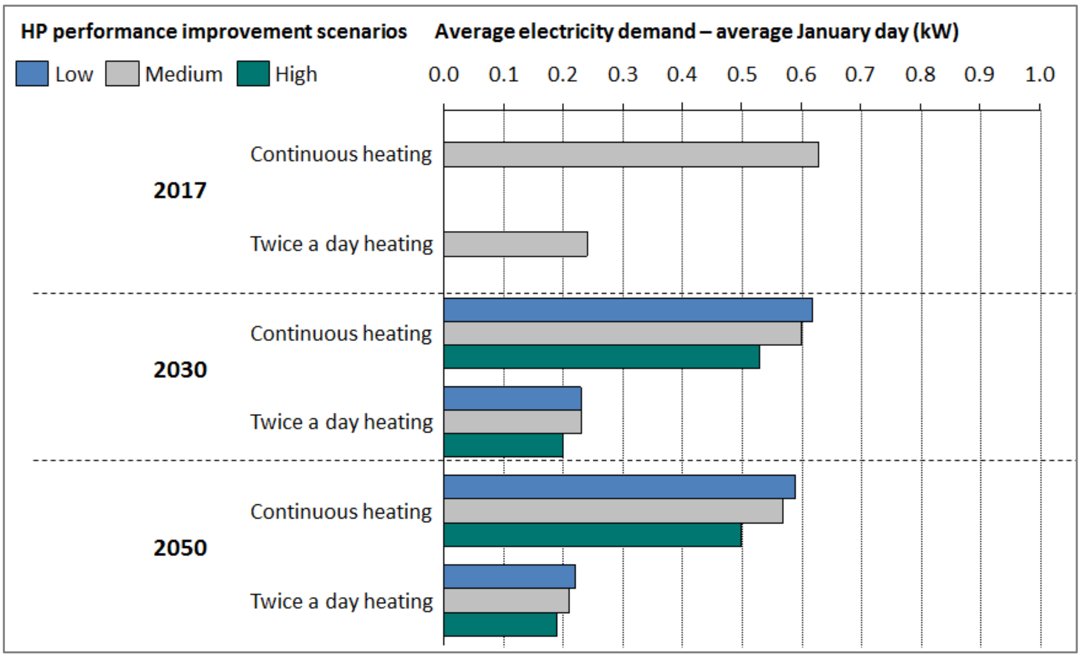
The technical modelling underlying the results presented so far in this report is based on assumptions relating to the HHP systems which are currently available. This section explores how various innovations in heat pump technology and other aspects of hybrid systems could impact the future performance of HHPs, in terms of the key performance metrics.

6.5.1 Impacts of heat pump performance improvement

The first innovation area considered is the heat pump itself. Improvements to COPs could be achieved through various innovations, including inverter driven technology and alternative refrigerants. High, medium and low scenarios capturing the potential impacts of these improvements on COPs of future heat pumps were set out in section 5.2; these scenarios form the basis for the results presented below. The maximum improvement scenario (the 'high' scenario) would see efficiency improvements of 18% by 2030 and 25% by 2050, compared to 2017 values.

Figure 6-18 shows how the average electricity demand from a HHP system on an average January day would change over time, under the different scenarios. Results are shown for the default case of continuous heating in a semi-detached house. Average electricity demand values are lower for the twice a day case than for the continuous case, as the heat pump can meet less of the overall heat demand.

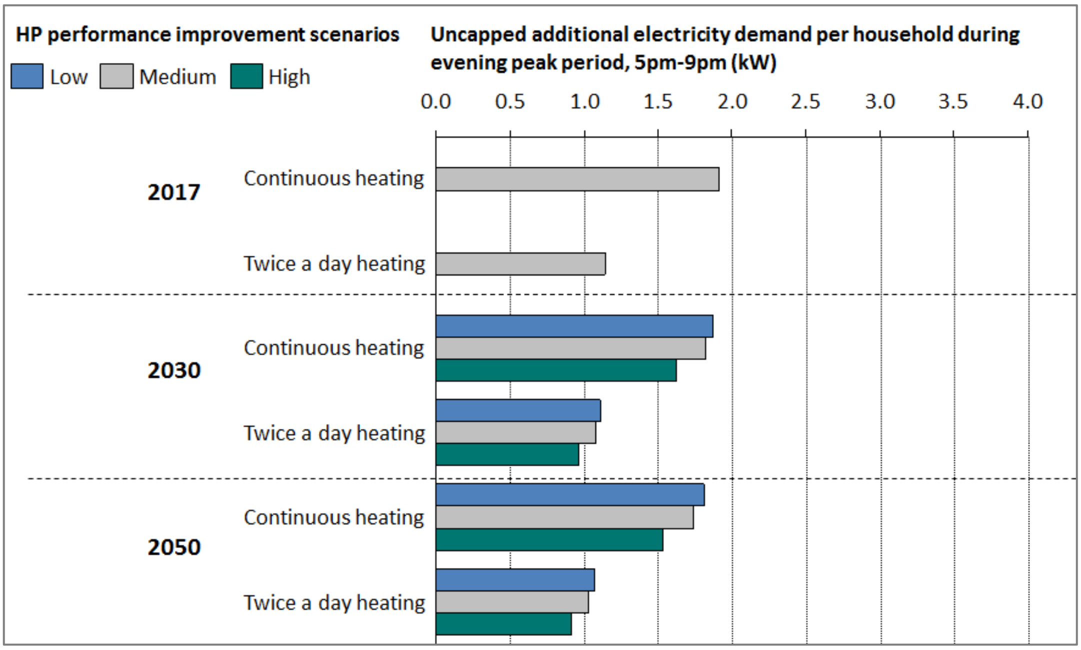
Figure 6-18 Average electricity demand from a HHP on an average January day (typical semi-detached), for low, medium and high heat pump performance improvement scenarios



The results show that improvements in COP can bring reductions to the average electricity demand from a hybrid system; the maximum reduction between 2017 and 2030 in the high improvement scenario is around 0.1 kW for the continuous case, and around 0.05 kW for the twice a day case. For the improvement scenarios shown, further improvements to COP after 2030 are assumed to be relatively low (see section 5.2.1), and therefore the additional demand reductions seen in 2050 are very small.

Figure 6-19 shows the impact of the different COP improvement scenarios on the peak electricity demand from a HHP system (operating in a parallel mode) during the evening peak period on a peak winter day. Note that the boiler would meet a significant share of the heat demand at peak times on a peak day for the twice a day heating profile.

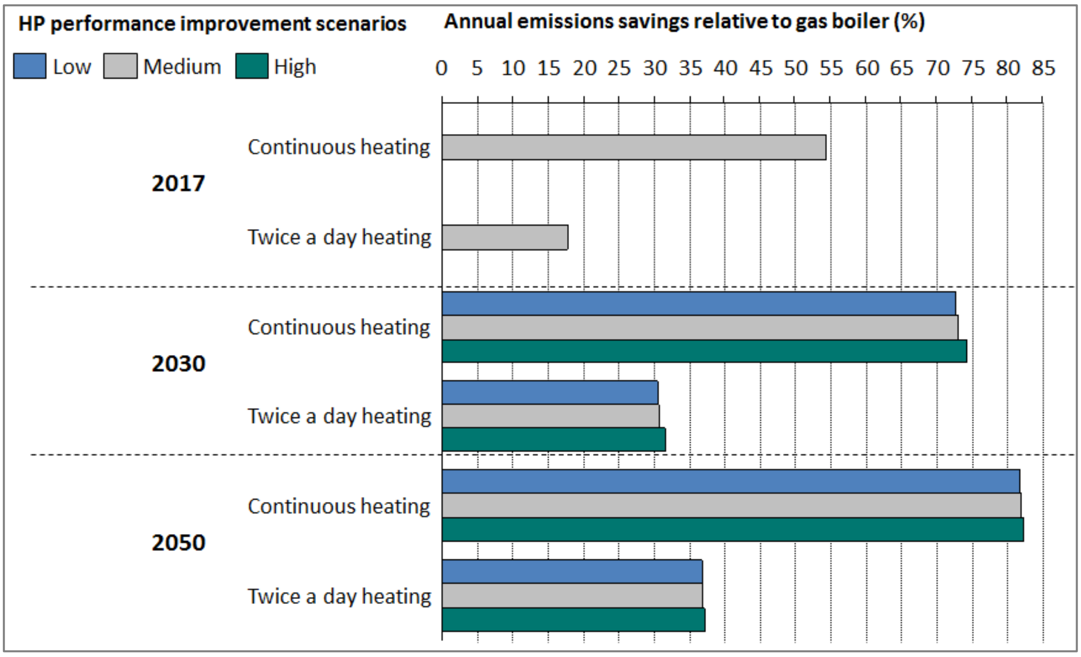
Figure 6-19 Maximum additional electricity demand from a HHP during the evening peak period on a cold January day (typical semi-detached), for low, medium and high heat pump technology innovation scenarios



The potential impacts of COP improvements on the peak electricity demand are not much greater than the impacts on average electricity demand; the maximum reduction between 2017 and 2030 in the high improvement scenario is approximately 0.2kW for the continuous case and for the twice a day case. The additional reduction by 2050 would be around 0.1kW (in the high improvement scenario).

Figure 6-20 shows the impact of the different COP improvement scenarios on the emissions savings from a HHP system for a typical semi-detached, relative to a gas boiler counterfactual. In general, the continuous heating profile achieves much higher savings than the twice a day heating profile, due to the higher share of heat demand met by the heat pump (see Figure 6-15 and Figure 6-16 in section 6.3).

Figure 6-20 Annual emissions savings of HHP relative to gas boiler in a typical semi-detached house, for low, medium and high heat pump technology innovation scenarios



The results shown in Figure 6-20 indicate that, while the potential emissions savings from HHPs could increase significantly between 2017 and 2050 (due to decarbonisation of UK electricity generation), improvements to heat pump performance are unlikely to have a great impact on potential savings. The maximum impact of the improvement to COPs is seen in the continuous heating case in 2030: under the high improvement scenario, the emissions savings are 74.4%, compared to 72.8% in the low improvement scenario. This difference corresponds to a 16% difference in the efficiency improvements on current values, between the two scenarios.

Overall, innovations leading to improvements to COPs are unlikely to make a significant difference to performance of HHPs, particularly in comparison to the differences in performance for different hybrid configurations (such as different heating schedules, emitter sizes and heat pump sizes). However, other innovations could make more of a difference to performance, either across the range of different configurations, or for particular modes of operation.

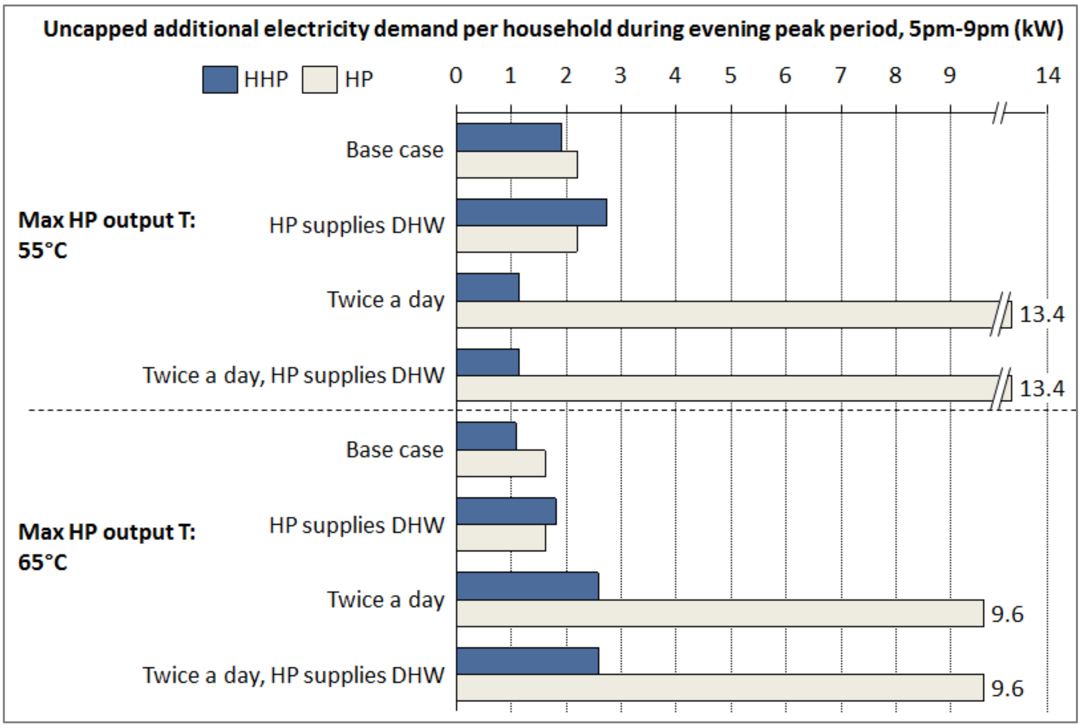
6.5.2 Impacts of increasing maximum heat pump output temperatures

The maximum output temperature of a HP can be a key constraint in meeting high levels of heat demand which, depending on the heating schedule followed, may occur infrequently (e.g. on very cold days) or more regularly (i.e. under non-continuous heating schedules). As such, increases in maximum HP output temperature, alongside improved performance at higher temperatures, could enable a greater share of the annual heat demand to be met by the HP component of a HHP. Using new refrigerants could help to achieve this.

Figure 6-21, Figure 6-22 and Figure 6-23 show the modelled performance parameters for key HHP and HP configurations with different maximum output temperatures (55°C representing current technology, and 65°C representing the innovation), in a typical semi-detached house. The HHPs are assumed to operate in parallel mode. The modelled COPs for the 65°C HPs are significantly higher for the same operating conditions, compared to the 55°C HPs, at 3.3 compared to 2.0 at an external T of -6°C, flow T of 45°C and return T of 40°C[31].

Carbon emissions reduction is shown for 2030. Daily CO_2 emissions profiles for 2017[32] were scaled down to meet the projected annual domestic consumption-based grid emissions factor for 2030[33]. Note that these profiles may change shape if the electricity portfolio significantly changes by 2030.

Figure 6-21 Uncapped additional electricity demand during evening peak for HHPs and HPs with different maximum output temperatures, under different heating schedules in a typical semi-detached house (assumes electric resistive backup in the standalone HP case)



31 Note: COP values for higher T HPs are calculated based on the performance of HPs using R134a, which is currently used only in larger HPs for industrial applications.
32 Calculated on a half hourly basis based on recent generation data and emissions factors
33 BEIS, March 2017, Table 1 of the Treasury Green Book supplementary appraisal guidance.

Figure 6-22 Share of annual heat demand met by HP component of HHPs with different maximum output temperatures, for different heating schedules in a typical semi-detached house

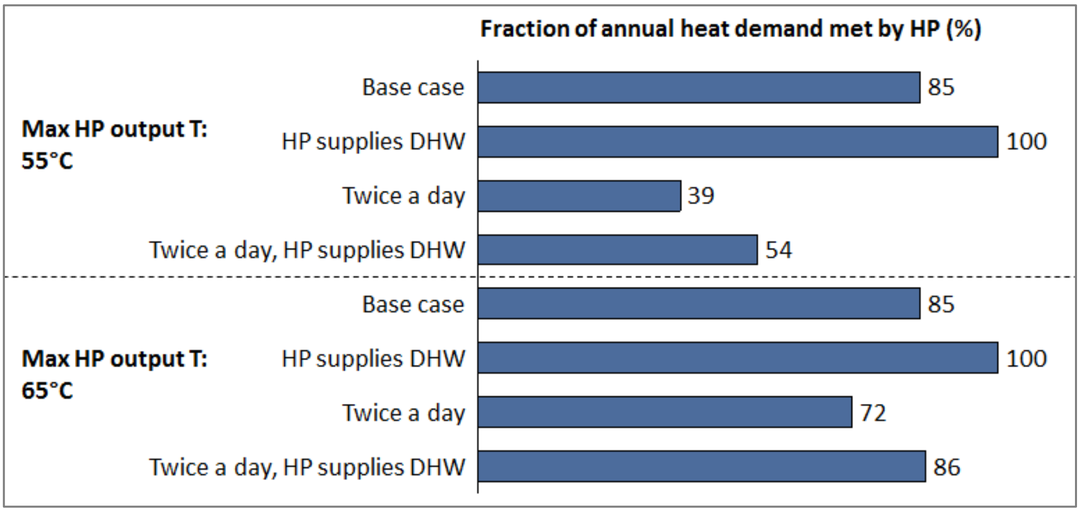


Figure 6-23 Projected annual emissions savings in 2030, relative to gas boiler for HHPs and HPs with different maximum output temperatures, and for different heating schedules in a typical semi-detached house

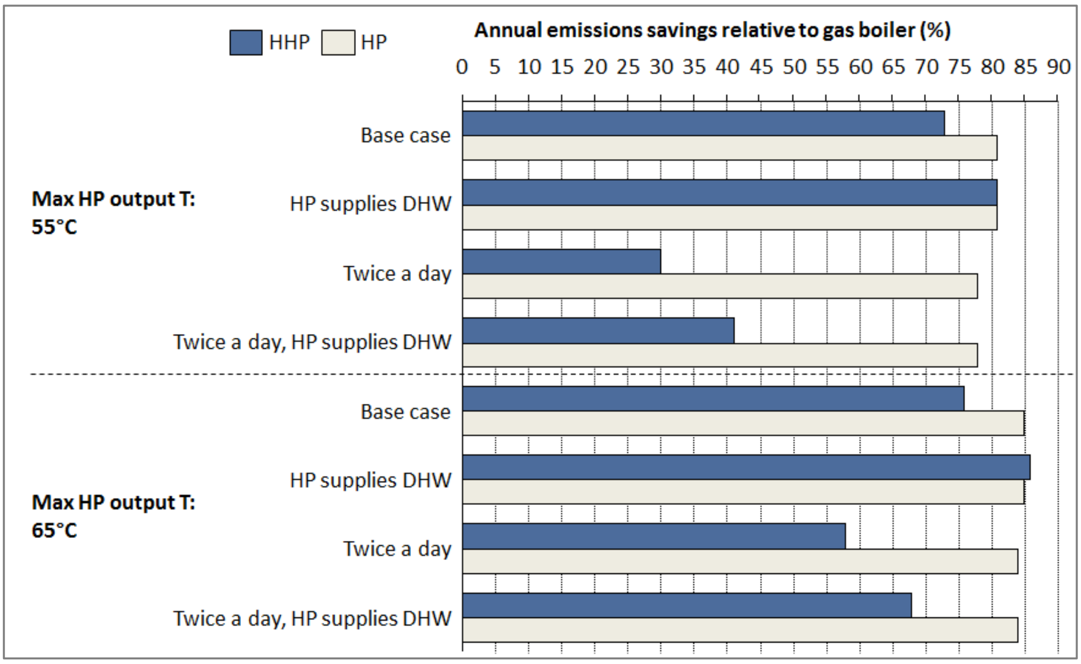


Figure 6-21 shows that higher T HPs could reduce the peak electricity demand from HPs at peak times, particularly for the twice a day case. For HHPs, the peak electricity demand would decrease for the continuous heating cases, but increase for the twice a day cases; this is due to the fact that the HP component would be able to meet a higher share of the heat demand during the evening heating period, due to the higher maximum output temperature. While this increases the additional electricity demand, it also increases the overall share of demand met by the HP component and therefore the emissions savings compared to the gas boiler, as shown in Figure 6-22 and Figure 6-23. Even in the twice a day heating case, emissions savings from HHPs in 2030 could reach 58-68% with higher temperature HPs (depending on the provision of DHW), as opposed to 30-41% for HPs with lower maximum output temperatures.

Overall, HPs with higher output temperatures (as well as higher COPs at higher temperatures) are likely to increase the benefits of HHPs, particularly in terms of emissions savings.

6.5.3 Impacts of innovation in thermal storage technology

This chapter has shown that using HPs and HHPs under a continuous heating profile, rather than a twice a day profile, maximises emissions savings as well as reducing the peak electricity demand. In theory, thermal storage could be used to smooth heat demand and run a HP or HHP on a relatively continuous profile, whilst delivering heat to the user on a twice a day profile, thus maximising the benefits.

Currently, a hot water-based thermal store with enough capacity to significantly smooth a twice a day heat demand profile on a winter day would have a prohibitively large footprint for many UK households. However, higher density, high capacity thermal storage could achieve this with a smaller footprint and, once affordable, could ultimately be a practical solution to improve the performance of heat pumps or HHPs while still using a twice a day heating profile.

Figure 6-24 shows the twice a day heat demand profile for a typical semi-detached house on a typical January day and a cold January day, and the heat demand profiles associated with filling a thermal store overnight and outside of the heating periods, to meet the twice a day profile.

The required capacity of thermal storage is of the order 60 kWh. If the store was a hot water cylinder storing water at 55°C, this storage profile would require a 1,400 litre cylinder, with volume 1.4 m^3 (excluding the volume of the insulation and the tank itself) which would clearly be prohibitively large for most homes. If high density thermal storage were to reduce the required volume by several times, however, such a capacity of thermal storage could become feasible.

Figure 6-24 Heating demand profiles for a typical semi-detached house; twice a day heating schedule profile and heat demand profile to fill a store to enable delivery of the twice a day schedule

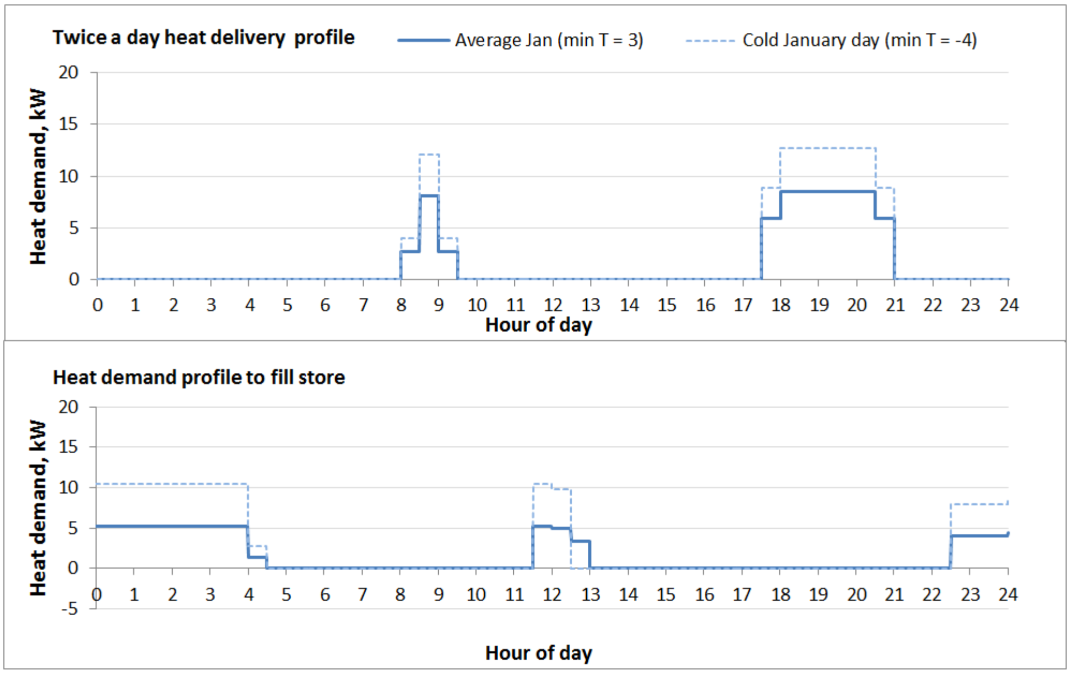


Figure 6-25 and Figure 6-26 show the peak electricity demand during the evening peak period, and the annual emissions savings relative to a gas boiler, for a 7kW standalone HP and a 5kW HHP, when a thermal store is used in this way. For comparison, the results are also shown for the continuous heating case, and for the twice a day case without storage. The HHP is assumed to operate with high T emitters, and use the boiler component for DHW generation, and the HP is assumed to operate with low T emitters, and use a small DHW cylinder to spread DHW demand throughout the day.

Figure 6-25 Effect of thermal store use on uncapped additional electricity demand during evening peak period, from HHPs and HPs following different heating schedules in a typical semi-detached house (assumes electric resistive backup in the standalone HP case)

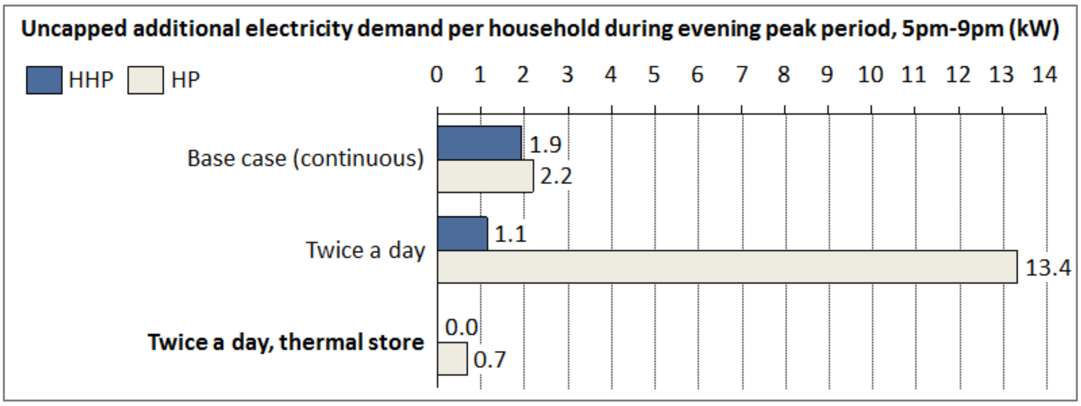
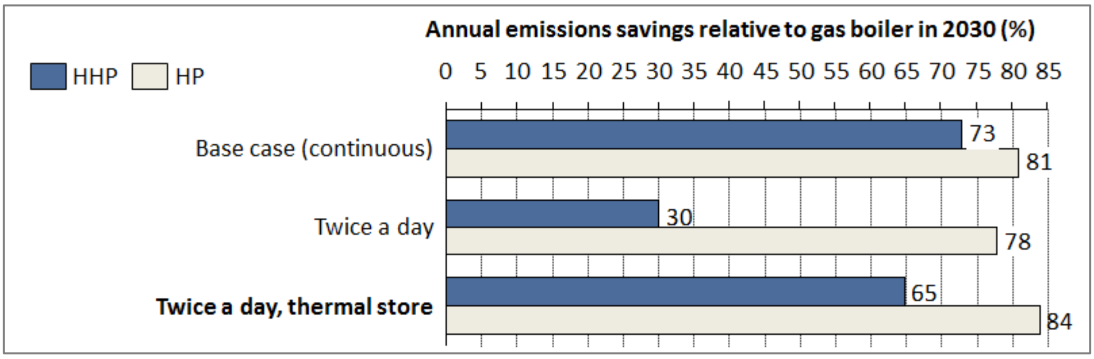


Figure 6-26 Effect of thermal store use on annual emissions savings in 2030 relative to a gas boiler, for HHPs and HPs following different heating schedules in a typical semi-detached house



As shown in the results in Figure 6-25, using a sufficiently sized thermal store (i.e. of the order 60 kWh) could eliminate the additional electricity demand in the evening peak period in the HHP case, as the HP component does not run in this period, and the DHW is provided by the boiler. Similarly, the electricity demand in this period is drastically reduced in the HP case, as the only demand comes from the generation of DHW, which occurs throughout the day. Note that the peak HP electricity demand on the ‘peak day’ in a typical year would occur between 3.30am and 4am, reaching 8.5 kW in the HP case and 1.5 kW in the HHP case. Ultimately, this new peak in demand could itself cause network loading problems, although this would depend on the uptake of HPs with thermal storage as well as diversity effects.

The results shown in Figure 6-26 suggest that running the heat pump primarily overnight leads to significant emissions savings, in both the HHP and HP cases. However, the standalone HP still delivers an additional 19% saving vs the gas boiler counterfactual, compared to the HHP (partly due to the difference in how DHW is supplied, and partly due to the use of low T emitters in the HP case and high T emitters as in the HHP case). Enabling the HP component to meet some of the DHW demand would increase the emissions savings for the HHP case. However, given that the maximum HP additional demand is so low in the evening period when the thermal store is used, from a performance perspective there would be little to no benefit of using a HHP over a HP if storage of this scale became affordable and practical.

6.5.4 Impacts of control strategy innovation

With increasing concern from electricity Distribution Network Operators (DNOs) around the high loading of cables and substations, and the high costs of reinforcements to local networks, stakeholders across the heat pump industry are currently exploring options to enable HPs (including HHPs) to respond to load control signals (e.g. from the DNO or from an aggregator), to temporarily reduce the heat pump output according to the needs of the local grid. The Greater Manchester Smart Energy trial of 550 HPs is testing the impacts of various demand response events on aggregated peak demand, and similarly, the FREEDOM project will simulate DSR events as part of their trial of 75 HHPs.

One possible strategy to reduce the additional load on the electricity network at peak times from HHPs would be to send a signal forcing the HP component to turn off at peak times (i.e. between 5pm and 6pm, or during the whole of the evening period e.g. 4pm-9pm).

This would force the HHP to use the gas boiler to meet the heat demand, and as such, would be likely to affect the emissions savings, depending on the electricity grid emissions at peak times and on the relative efficiencies of the HP and the boiler.

Figure 6-27 illustrates the modelled impacts of two peak-shaving strategies on annual emissions savings compared to a gas boiler, for three different HHP configurations in a typical semi-detached house with high T emitters. The first two cases assume that the boiler component of the HHP meets the DHW demand, and the latter assumes that the HP meets DHW demand when possible. For the 2017 values, the carbon intensity of electricity was calculated on a half hourly basis based on recent generation data and emissions factors. For the 2030 values, daily CO_2 emissions profiles for 2017 were scaled down to meet the projected annual domestic consumption-based grid emissions factor for 2030[34]. Note that these profiles may change shape as the electricity portfolio changes through to 2030.

The modelling assumes that the boiler counterfactual and the combination boiler included in the HHP have an efficiency of 81%. Figure 6-28 shows the equivalent scenarios but with a boiler efficiency of 90%. In both cases, the peak-shaving scenarios have lower emissions savings than the no peak shaving scenarios, demonstrating that even during peak hours, running the heat pump has lower emissions than running the boiler.

For both peak-shaving strategies, the demand from the HP is assumed to drop to zero during the specified time period for every day of the year, in order to avoid increasing the local network loading. In reality, it is unlikely that this would be required every day, so this represents the worst case scenario in terms of the impact on emissions savings. Even under these assumptions, the results suggest that HHPs could still deliver significant savings compared to a gas boiler; in 2017, the 4pm-9pm peak-shaving scenario could

[34] BEIS, March 2017, Table 1 of the Treasury Green Book supplementary appraisal guidance.

deliver 42%-45% savings, in the base case (continuous heating) depending on the boiler efficiency, increasing to 59-60% in 2030.

The reduction in emissions savings resulting from the 4pm-5pm peak-shaving strategy would be up to 10% for the most extreme peak-shaving scenario, and up to 15% in 2030. The results emphasise the fact that continuous heating can achieve much higher emissions savings than the twice a day heating schedule (based on an electricity emissions intensity profile with a similar shape to that based on the current UK generation mix).

Figure 6-27 Annual emissions savings from HHPs in a typical semi-detached house, compared to a boiler (81% efficient), with different peak-shaving strategies

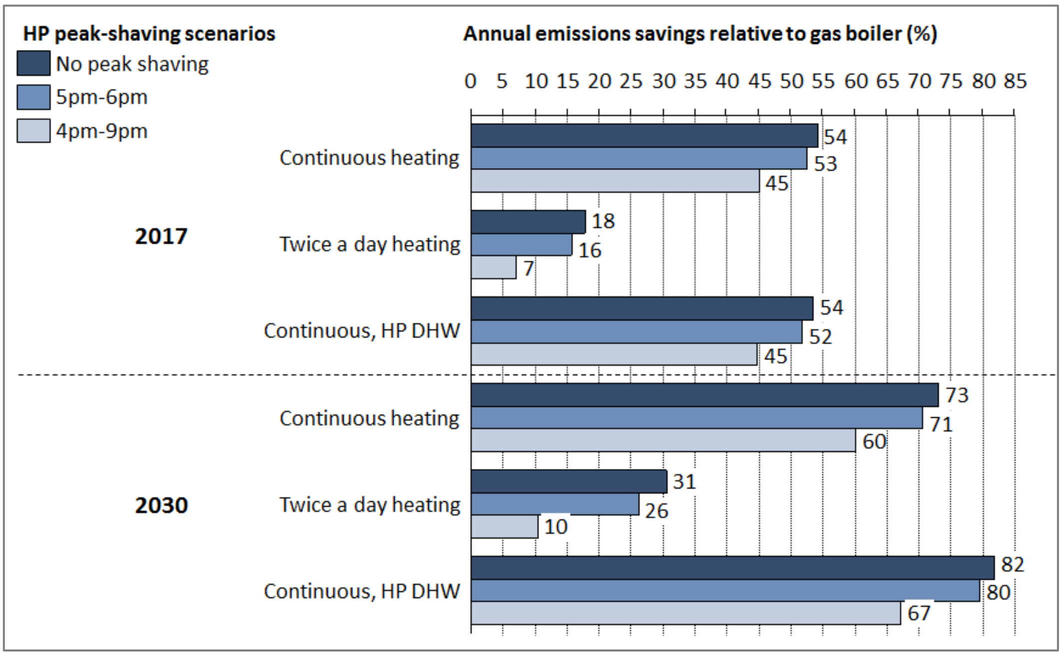
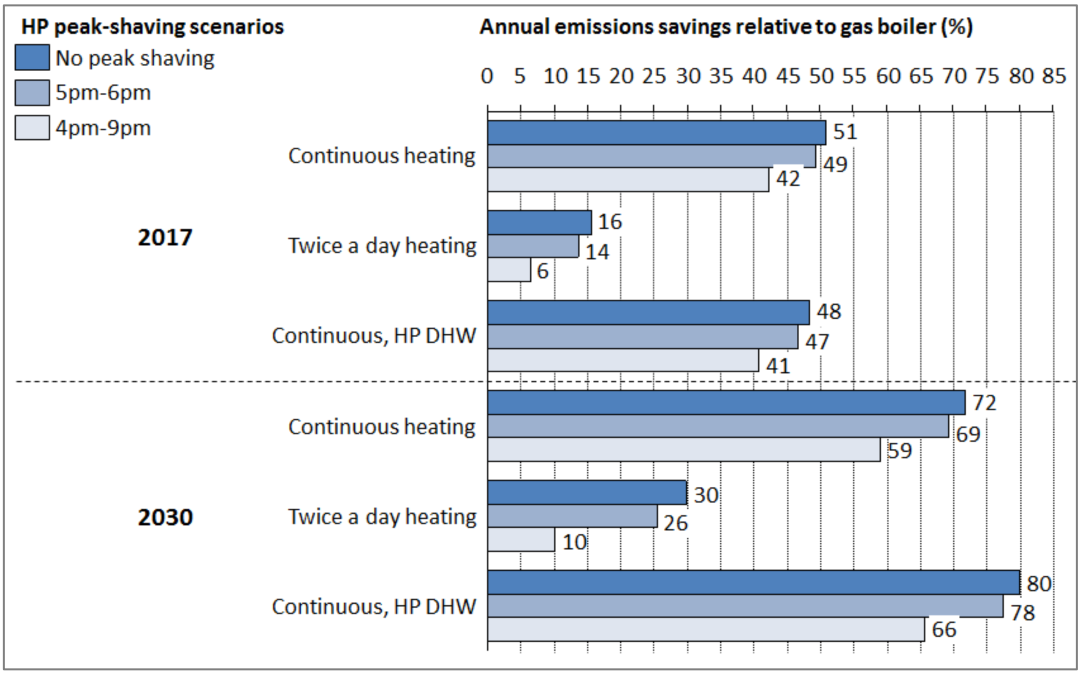


Figure 6-28 Annual emissions savings from HHPs in a typical semi-detached house, compared to a boiler (90% efficient), with different peak-shaving strategies



7 Lifetime costs and emissions of domestic HHPs vs electric-only heat pumps and gas boilers

7.1 Key assumptions

The lifetime cost and carbon emissions comparison is based on the cost and performance data gathered, modelled and analysed as described in the preceding sections. As part of the comparison, the potential impact of the **range of current cost values** and the **range of cost reduction scenarios** presented in Section 4 is studied.

Figure 7-1 summarises the central capital cost assumptions in 2017 for the different systems included in the cost analysis. The boiler is by far the cheapest technology, but the standalone heat pump is assumed to be around £2,000 more costly than the base case HHP system, which is assumed to avoid the requirement for low T emitters (radiator replacement).

Figure 7-1 Upfront costs of different heating systems in 2017, for a typical semi-detached house

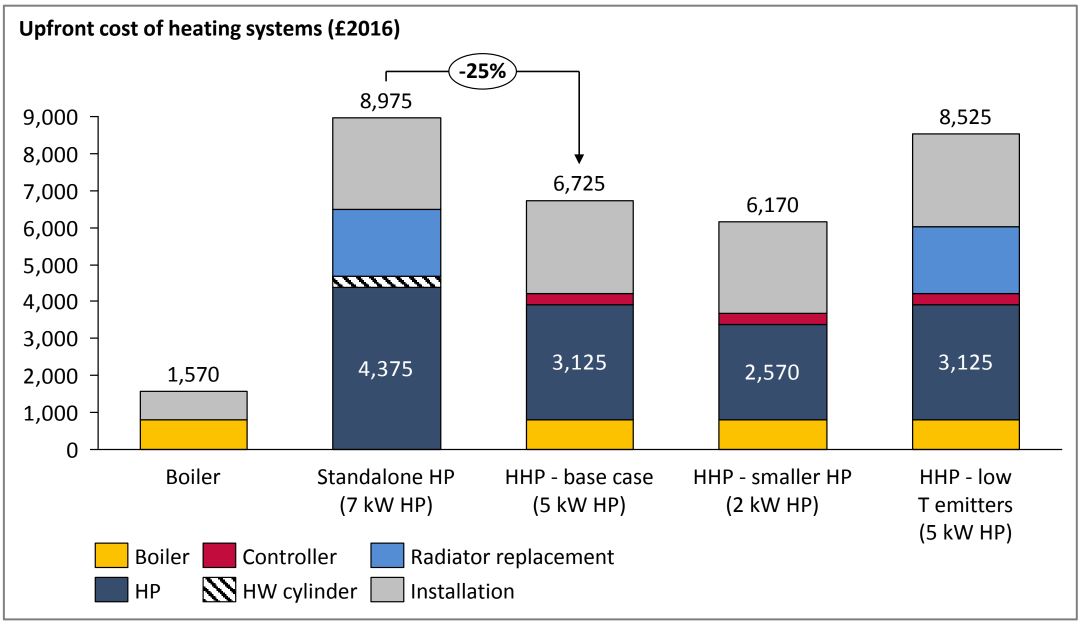


Figure 7-2 shows the possible range on the upfront costs of different heating systems for a typical semi-detached house in 2017 and 2030, reflecting the different values found in the literature, and based on the industry consultation (refer to Section 4.4 for more detail).

Figure 7-2 Range of upfront costs of different heating systems in 2017, and 2030 for a typical semi-detached house

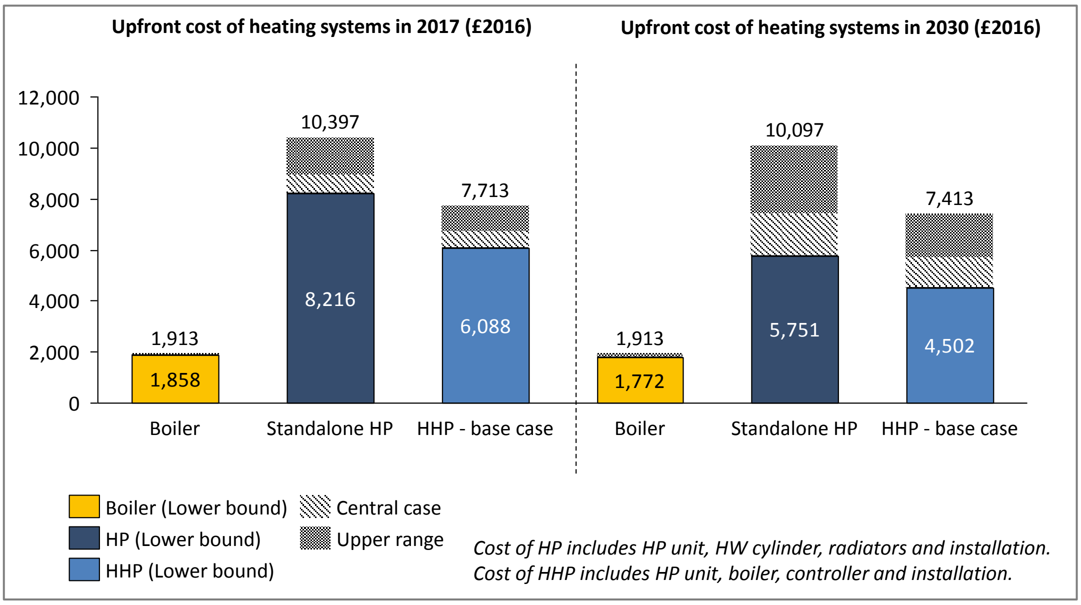


Figure 7-3 shows the annual fuel costs in 2017 for the various system configurations (for a typical semi-detached building, with the continuous heating mode as the base case). Fuel costs for HHPs following a continuous heating schedule are slightly lower than for gas boilers, and over £100 lower than for standalone HPs following a continuous heating schedule.

Figure 7-3 Annual fuel costs in 2017 for different heating systems in a typical semi-detached house

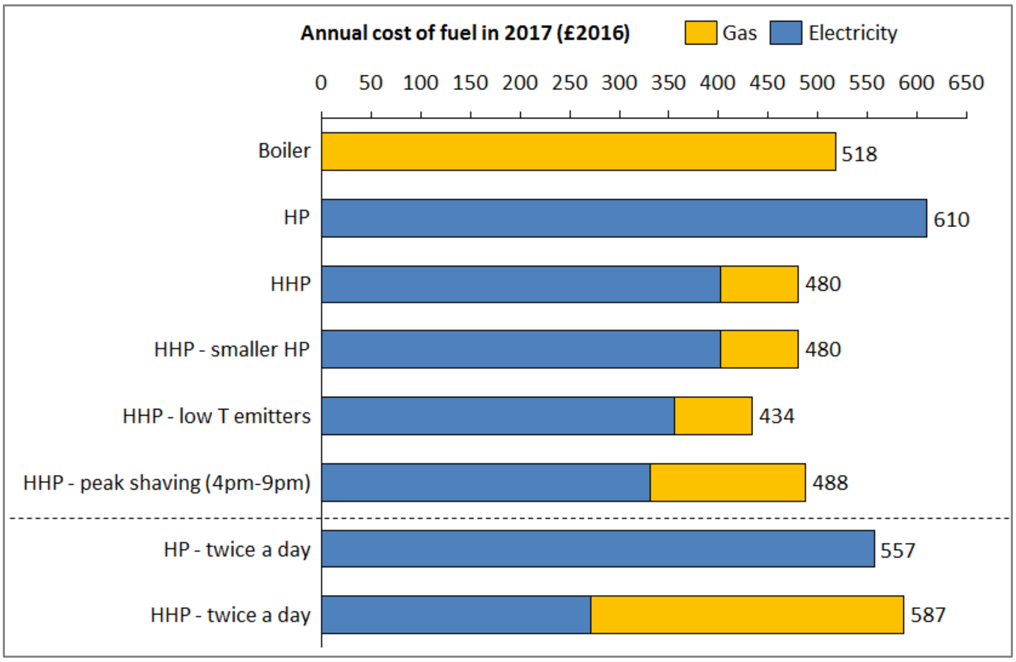
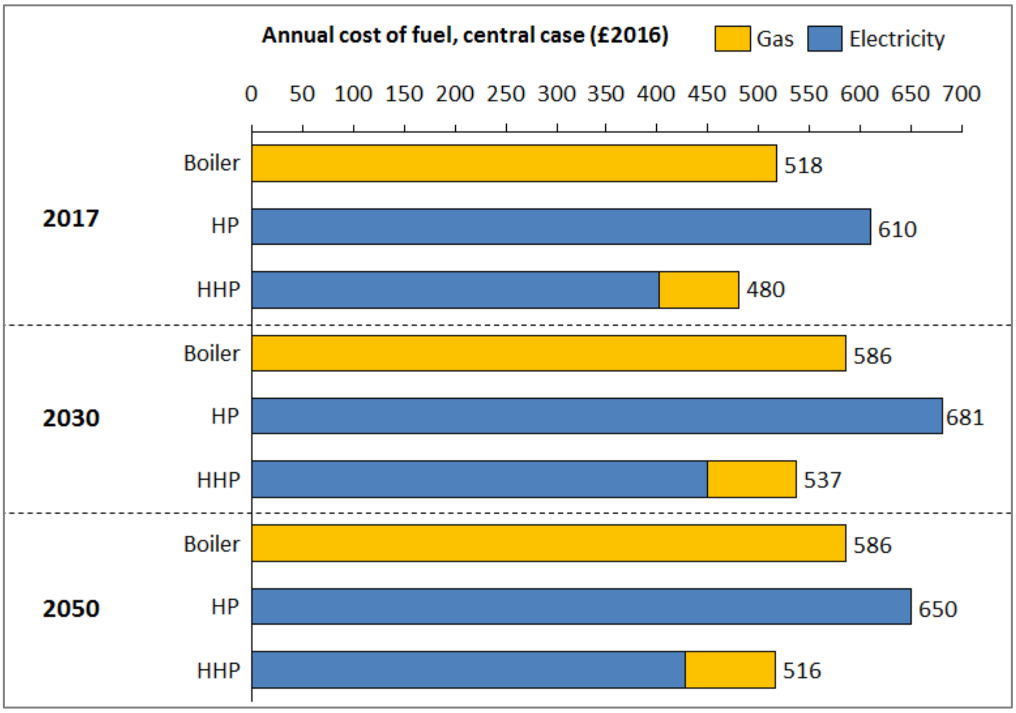


Figure 7-4 shows how the annual fuel costs change over time under the central scenarios for costs and innovation. Under this scenario, electricity and gas costs per kWh are both assumed to increase to 2030 and then level out through to 2050. As such, the total fuel costs for HPs and HHPs increase between 2017 and 2030, and come down again in 2050 as a result of incremental improvements to HP technology.

Figure 7-4 Annual fuel costs in central innovation and cost scenarios for different heating systems in a typical semi-detached house



The full set of assumptions as used in the lifetime cost and carbon emissions comparison is given in the Appendix, as noted below:

- Product and installation costs: Table 9-2
- Product and installation cost projections (Low/Medium/High): Table 9-3
- Financial assumptions: Table 9-4
- Fuel costs: Table 9-5[35]
- CO_2 emission factors: Table 9-6

A variety of scenarios are presented, with assumptions as defined in Section 6.1. As a reminder, the default assumptions for the HHP and HP cases are as shown in Table 6-1 on page 61. Key aspects to note are the different assumptions between default HHP and HP cases for HP component sizing, DHW provision method and emitter type. These differences have an important impact in the lifetime cost comparison presented below.

7.2 Net present cost

Figure 7-5 shows a comparison of the net present cost (NPC) of the HHP, standard HP and Gas boiler options in the Base case of a Typical semi-detached building archetype, following a twice a day heating schedule in the gas boiler case, and a continuous heating schedule in the HP and HHP cases (configurations as per the default cases set out in Table 6-1). The NPC is calculated using a 3.5% discount rate, and includes all capital costs and running costs (as outlined above) over a 15 year economic lifetime. The NPC is presented for three installation years of 2017, 2030 and 2050, and for three cost scenarios:

[35] Carbon prices are not included in the analysis.

- Lowest cost = Low current cost, High cost reduction
- Central cost = Central current cost, Central cost reduction
- Highest cost = High current cost, Low cost reduction

For the Typical semi-detached building, in 2017, the NPC of the Gas boiler counterfactual is approximately £10,000. The NPC of the HHP ranges from £14,000 to £16,000 as a result of the cost range applied, and that of the HP ranges from £18,000 to £20,000. It is therefore clear that in simple lifetime cost terms, the **Gas boiler is the lowest cost option** by several thousand pounds. It is also clear that the **HHP option is substantially more cost-effective in lifetime cost terms than the HP**. The key reasons for this are:

- The smaller HP component of the HHP (5 kW) relative to the HP case (7 kW) results in a cost reduction of approximately £1,300;
- Replacement of emitters is optional in the HHP case, and is not implemented in the Base case, resulting in a further cost reduction of £1,800 versus the HP case;
- Purchase of a hot water storage tank is not required (since the Gas boiler provides all DHW), resulting in a further cost reduction of £300;
- The cost of the additional equipment required – the Gas boiler and the controller – is £1,100, meaning the **total capital cost is approximately £2,000 lower in the HHP case versus the HP case;**
- The electricity to gas price ratio over the period 2017 to 2050 ranges between approximately 4 and 5; since the typical SPF achieved by the HP is less than 3 in the winter months, gas heating remains lower cost than electrical heating using the HP over the whole period 2017-2050; since the DHW demand is met by the Gas boiler in the HHP case, and this corresponds to 15% of the total heating demand, this leads to substantial ongoing cost savings of more than £100 per year, resulting in **further lifetime cost savings due to reduced fuel costs in the HHP case relative to the HP case in the region of £2,000**.

For installation in later years, the Gas boiler option increases in cost, due to the increase in the gas price over this period. However, the Gas boiler remains the lowest cost option in all cases.

For the HHP and HP options, the range between the lowest cost and highest cost scenarios increases due to the variation between the cost reduction projections. In all cases, the HHP is at least £2,800 lower in terms of lifetime cost than the HP. In 2050, in the lowest cost scenario for the HHP (by which time the product and installation cost of HHPs and HPs has reduced by 30% relative to 2017), the lifetime cost of the HHP option falls to within £2,000 of the Gas boiler. In most future scenarios, however, the lifetime cost of the HHP is several thousand pounds higher than for the Gas boiler.

Figure 7-5 Net present cost comparison: Base case (Typical semi-detached)

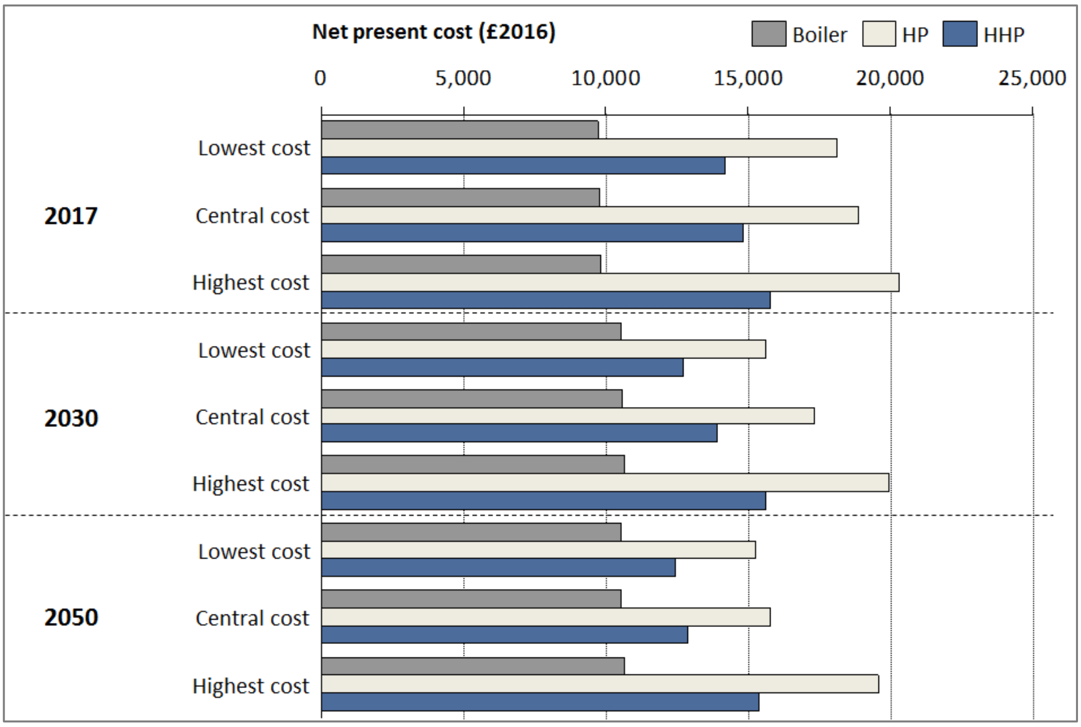


Figure 7-6 shows the corresponding results for the Smaller HP case, in which the size of the HP component of the HHP is reduced to 2 kW (versus the 5 kW Base case), whereas the size of the HP counterfactual remains at 7 kW.

As demonstrated in Section 6, the reduction in size of the HP component for the HHP still allows nearly all the space heating demand to be met by the HP (in the case of continuous heating). As such, the ongoing fuel cost is essentially unchanged versus the 5 kW HHP Base case. However, the capital cost is reduced, due to the smaller HP purchased. Using the cost estimates derived from the consultation data, as presented in Section 4 (and in Table 9-2 in the Appendix), the cost saving of down-sizing from a 5 kW HP to a 2 kW HP is quite limited, at around £550 in the Central case in 2017. This leads to an overall reduction in the NPC of £550 versus the Base case.

It is worth noting that only a single product under 5 kW was identified in the consultation and literature review, and hence the cost estimate for this size range is reliant on that data point. While it is unlikely to be the case that the product cost could reduce in line with the size reduction at these small scales, due to the fixed cost elements of the product, it may be expected that the entry into the market of a greater range of small (i.e. < 5 kW) HP products to cater for the HHP market could lead to a reduction in the cost versus that presented here. This would lead to a reduction in the lifetime cost of the HHP in the Smaller HP case, and present an additional advantage over the standard 7 kW HP.

Figure 7-6 Net present cost comparison: Smaller HP case for HHP

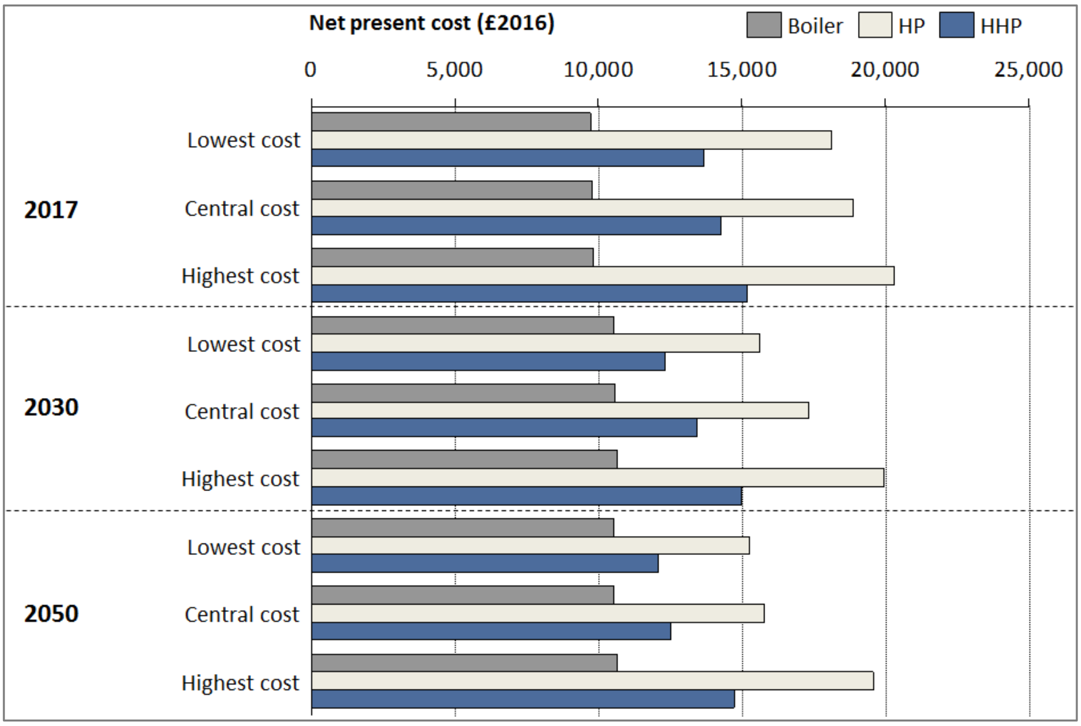
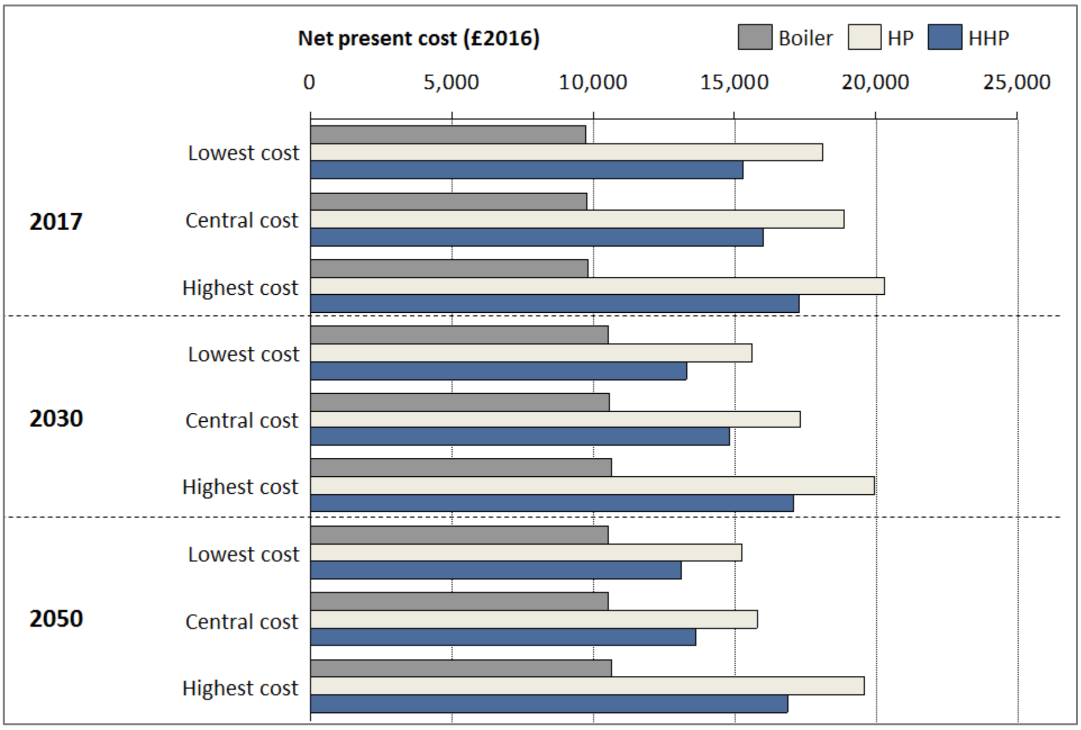


Figure 7-7 shows the NPC variations for the case of Low T emitters for the HHP case (matching the counterfactual HP case, which always assumes that Low T emitters are used). As described in Section 6, the use of Low T emitters in the HHP case is optional, since the Gas boiler can be used to ensure sufficient supply temperature when a flow temperature greater than the HP can provide is required, but allows a higher SPF to be achieved by the HHP. This brings a reduction in the carbon emissions associated with the HHP, but also a reduction in the fuel cost resulting from the more efficient use of electrical input.

The NPC results suggest, however, that the fuel cost savings are outweighed by the additional cost associated with the replacement of emitters, at £1,800. Figure 7-7 shows that the NPC of the HHP option installed in 2017, in the Central cost scenario, increases from £14,800 in the Base case (as in Figure 7-5) to £16,000, an increase of £1,200. This suggests that the Low T emitters result in discounted lifetime fuel cost savings of around £600. Indeed, the use of Low T emitters leads to fuel cost savings in 2017 of around £50 per year.

Figure 7-7 also shows that the value of installing Low T emitters increases over time; the NPC of the HHP option installed in 2050, in the Central case, is £13,600, which is £700 higher than the NPC of the corresponding Base case (£12,900). This reduction is due mainly to the reduction in cost of installing Low T emitters (30% lower than the 2017 case in 2050 in the Central cost reduction scenario).

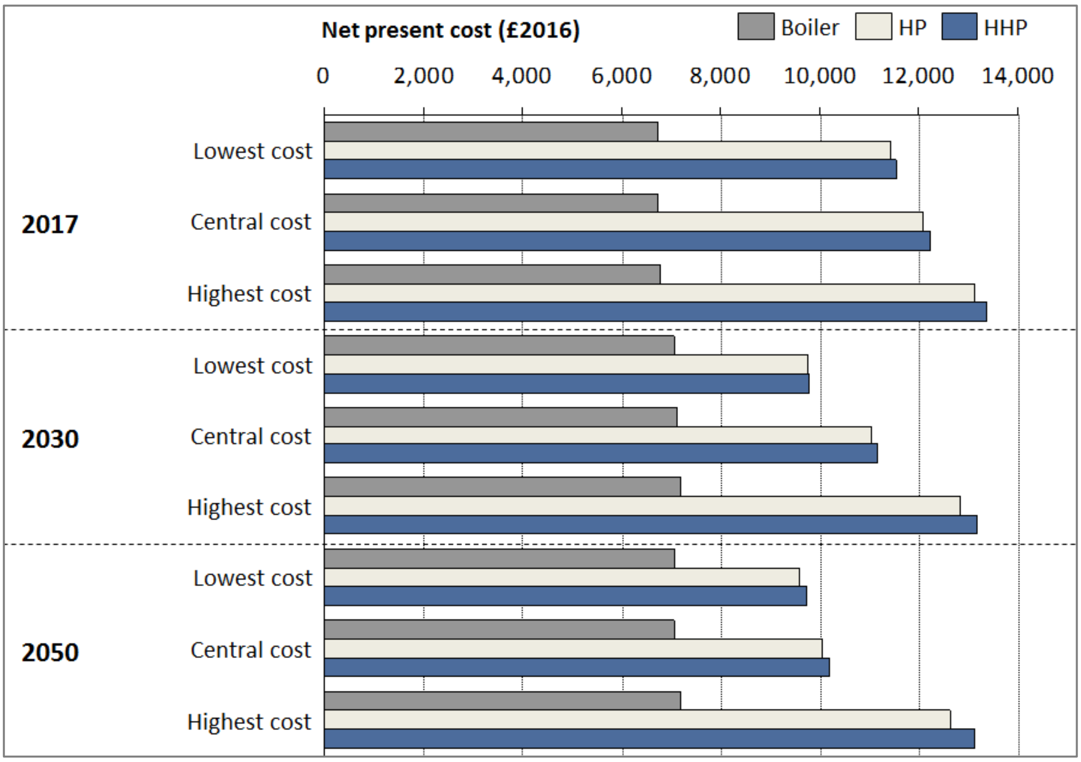
Figure 7-7 Net present cost comparison: Low T emitters case for HHP



Finally, Figure 7-8 shows the NPC results for the case of a Zero-carbon semi-detached home with low T emitters. The counterfactual HP case is different in this scenario. It is assumed in this scenario that the counterfactual HP is smaller in size (5 kW) than in the Base case (Typical semi-detached, 7 kW) due to the lower heat demand of this building type, and that no replacement of emitters is required since the building could be designed to operate using low supply temperatures and so low T emitters installed at point of construction. This means that the counterfactual HP case is more cost-effective than in the Base case; for 2017 installation in the Central cost scenario, the capital cost of the HP case is £5,900, versus £9,000 in the Base case. The corresponding capital cost for the HHP in the Zero-carbon semi-detached case is £7,800, now higher than the HP counterfactual due to the additional cost of the boiler and controller unit, and similar cost of the HP component. Note that the HHP heat pump component is assumed to be 3kW, but has a similar cost to the 5kW system used in the HP case, due to the higher £/kW for smaller systems.

As such, for the Zero-carbon semi-detached scenario, the NPC for the HHP option is very similar to, and even slightly higher than, the NPC for the HP counterfactual. The two options remain very similar in lifetime cost terms over the period to 2050, and across the different cost reduction scenarios. This suggests that for highly thermally efficient buildings such as the Zero-carbon semi-detached building, where the counterfactual HP is more cost-effective for the reasons described above, the HHP does not represent a more cost-effective alternative – in contrast to the Typical semi-detached building presented above.

Figure 7-8 Net present cost comparison: Zero-carbon semi-detached with low T emitters



In summary, the lifetime cost analysis has shown that for typical existing buildings (i.e. which are not highly thermally efficient) HHPs offer a substantial improvement in terms of cost-effectiveness relative to a standard HP counterfactual. The Gas boiler option, however, remains the most cost-effective in all scenarios and over the whole period to 2050.

As competing technologies in a decarbonising energy system, a key metric is then the level of carbon emissions reduction the HHP and HP options offer versus the Gas boiler option, and the cost of carbon savings. These metrics are explored in the following sections.

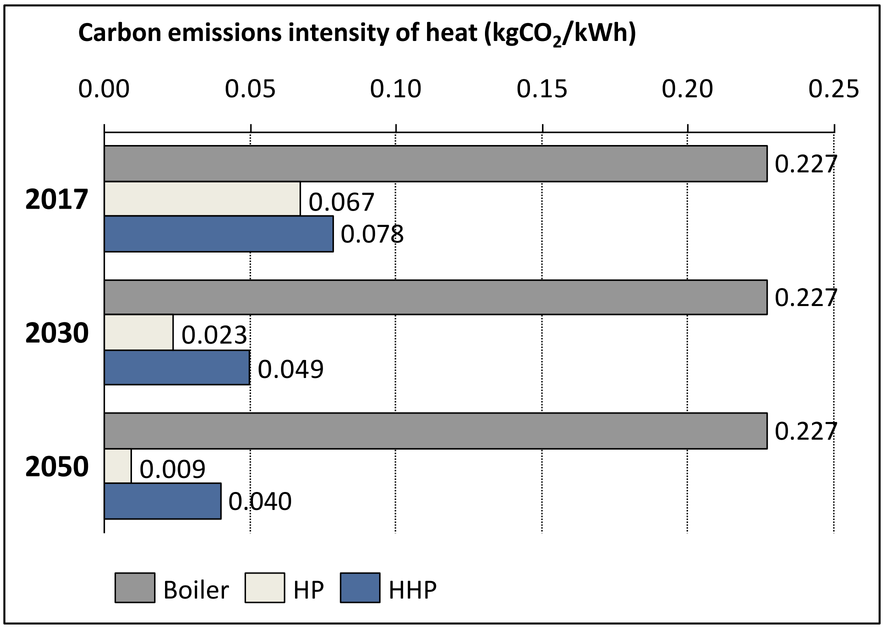
7.3 CO_2 intensity of heat

Figure 7-9 presents the carbon emissions intensity of heat (in terms of $kgCO_2$ per kWh heat supplied) for the three heating options, for the Base case of the Typical semi-detached building. The carbon intensity of heating using the Gas boiler option is 0.227 $kgCO_2$/kWh, substantially higher in all years than heating using the HHP or HP options and representing the baseline heating emissions.

For installation in 2017, the HHP and HP have very similar overall carbon emissions intensity, at 0.078 $kgCO_2$/kWh and 0.067 $kgCO_2$/kWh respectively. The majority of the difference is explained by the use of the Gas boiler for DHW heating in the HHP case, representing 15% of the total heating demand. Since the carbon emissions intensity of electrical heating is still significant in 2017, as the grid carbon intensity is substantially higher than zero (it is assumed in 2017 to be 0.290 $kgCO_2$/kWh), the 15% of heat demand met using gas in the HHP case does not lead to a large increase in carbon intensity versus the HP case. The small difference in carbon intensity of HHP and HP also reflects the fact that the HP efficiency is relatively low when supplying DHW (at a relatively high temperature of 55ºC), meaning that using the HP for DHW heating is more carbon intensive than using the HP for space heating, on average.

However, for installation in the later years, when the electricity grid is nearly fully decarbonised (grid electricity carbon intensity is assumed to fall to 0.117 $kgCO_2$/kWh by 2030 and 0.028 $kgCO_2$/kWh by 2050), the difference between the HHP and the HP is more pronounced. This reflects the fact that heating using the HP becomes very low carbon (0.009 $kgCO_2$/kWh by 2050), and even a 15% shift to gas heating to supply DHW results proportionally in a large increase in carbon intensity. The carbon intensity of the HHP option is nonetheless very low, at 0.040 $kgCO_2$/kWh in 2050.

Figure 7-9 CO_2 intensity of heat: Base case (Typical semi-detached)



The carbon intensity of heating for the HHP in the Smaller HP case, as shown in Figure 7-10, is almost identical to the Base case. This is because the smaller HP is still able to meet almost all the space heating demand – as shown in Figure 6-15 on page 76 – and hence the electricity and gas consumption is almost identical to the Base case.

In the case of Low T emitters for the HHP option, as shown in Figure 7-11, the carbon emission intensity of the HHP option improves slightly as a result of the higher average efficiency of the HP component, reducing from 0.078 $kgCO_2$/kWh to 0.073 $kgCO_2$/kWh in 2017.

Figure 7-10 CO_2 intensity of heat: Smaller HP case for HHP

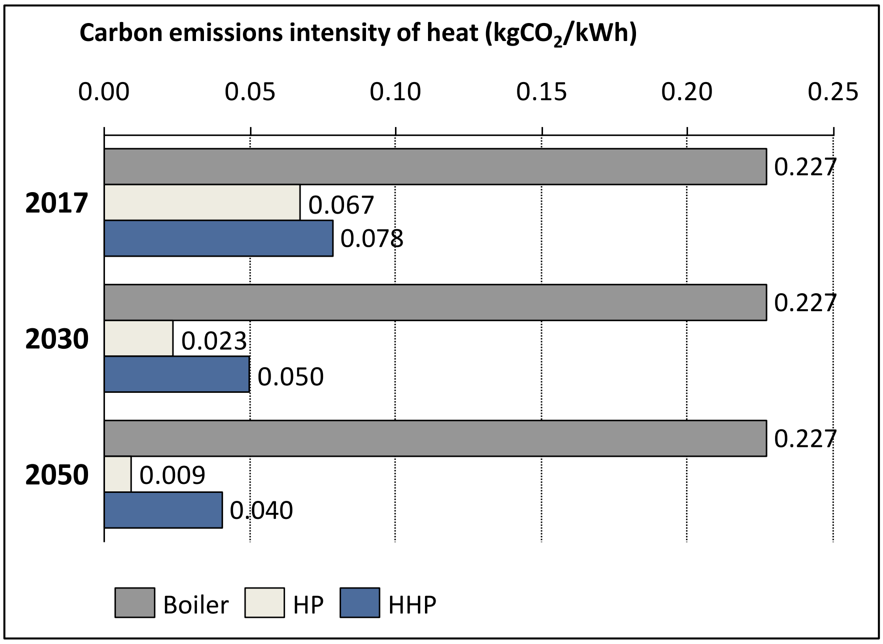
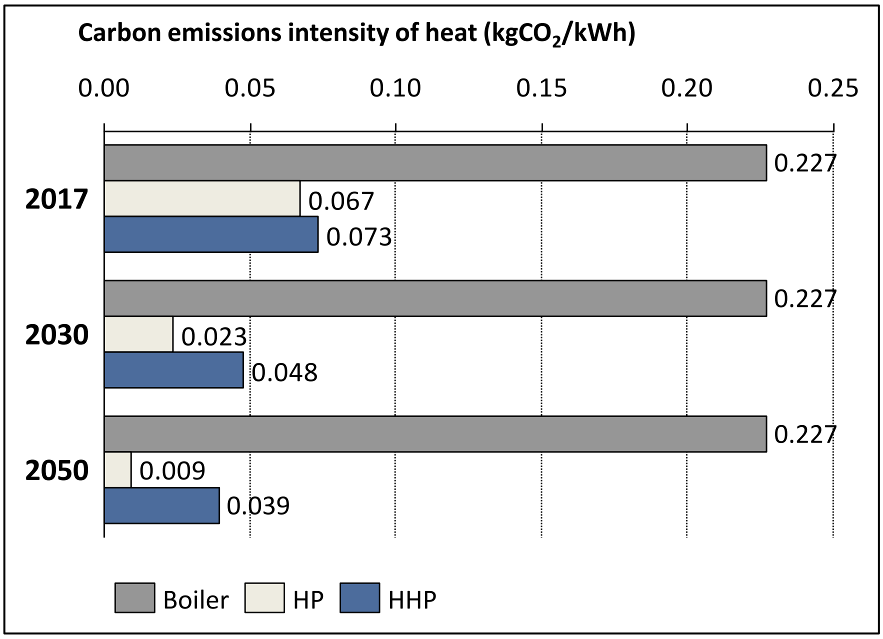
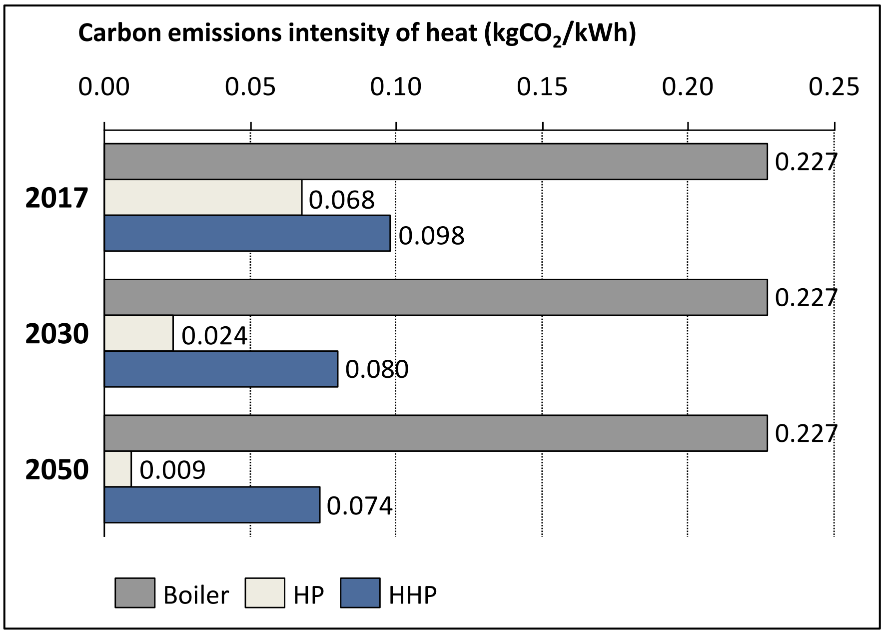


Figure 7-11 CO_2 intensity of heat: Low T emitters case for HHP



In the Zero-carbon semi-detached building, as shown in Figure 7-12, the average carbon intensity of heating in the HHP case is substantially higher than in the Base case, at 0.098 $kgCO_2/kWh$ in 2017, versus 0.078 $kgCO_2/kWh$ in the Base case. This is also substantially higher than for the HP case in the same building, at 0.068 $kgCO_2/kWh$. This is a result of the low space heating demand resulting from the high thermal efficiency of the building, which means that DHW accounts for a higher share of the total heating demand. Since the DHW is met by the gas boiler in the HHP case, this leads to higher average carbon emissions intensity. As for the other cases studied above, the difference between the HHP and HP becomes more pronounced as the grid decarbonises further.

Figure 7-12 CO_2 intensity of heat: Zero-carbon Semi-detached with low T emitters



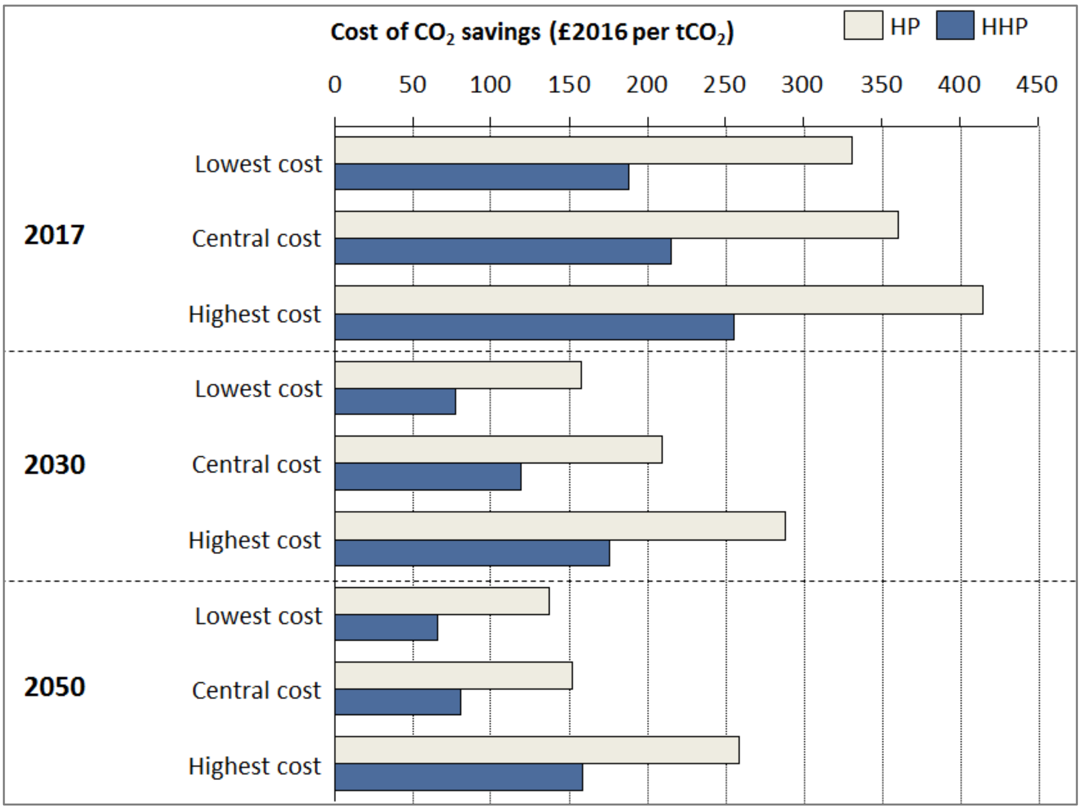
7.4 Cost of CO_2 savings versus Gas boiler

Combining the evidence on lifetime net present cost of the various heating options with the evidence on the carbon intensity of heating, it is possible to derive scenarios for the cost of carbon emissions savings of the HHP and HP options versus the Gas boiler case.

Figure 7-13 presents the scenarios for the cost of CO_2 savings for the Base case of the Typical semi-detached building. The cost of CO_2 savings is calculated as the NPC relative to the Gas boiler option, divided by the total lifetime carbon savings versus the Gas boiler option. In line with the substantially lower lifetime cost of the HHP option versus the HP option for the Base case, and the comparable reduction in carbon emissions intensity versus the Gas boiler option, the cost of CO_2 savings is significantly lower for the HHP than the HP for installation in all years.

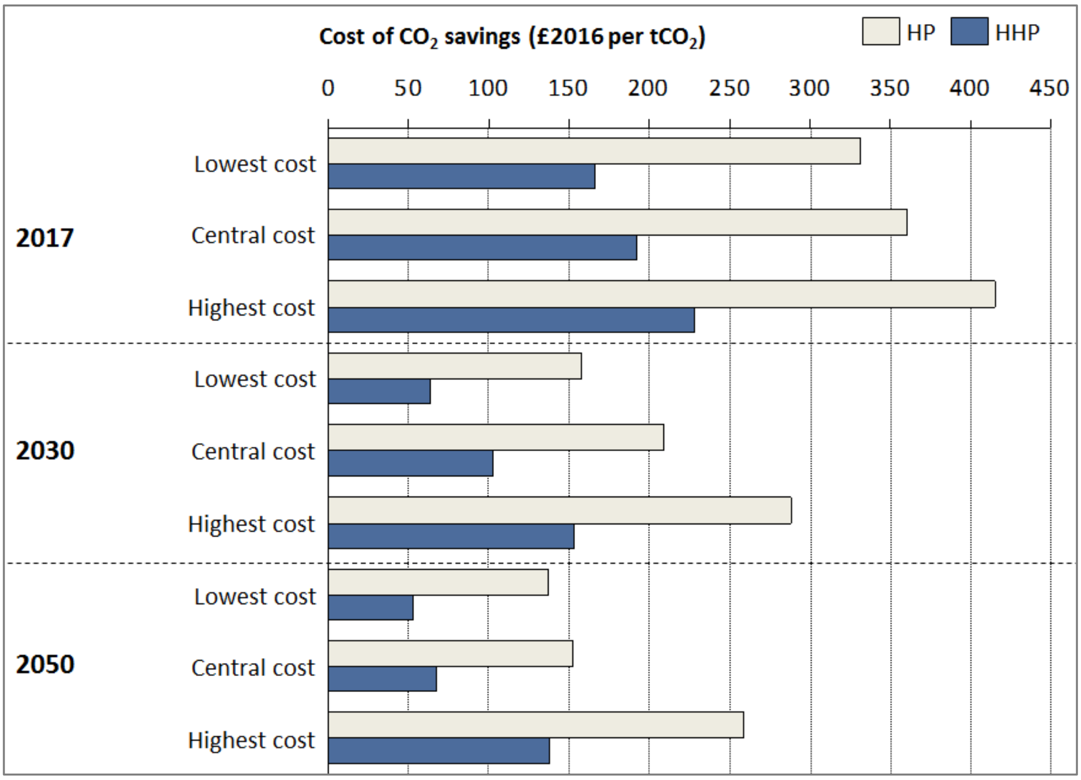
For installation in 2017, the cost of CO_2 savings for the HHP ranges from £190/tCO_2 to £255/tCO_2 across the range of cost scenarios, compared with £330/tCO_2 to £415/tCO_2 for the HP option. The cost of CO_2 savings reduces for both the HHP and HP options over time, as the product and installation costs reduce and the falling carbon intensity of the grid results in greater CO_2 savings. For installations in 2050, the cost of CO_2 savings for the HHP option falls as low as £65/tCO_2 in the lowest cost scenario, and to £80/tCO_2 in the central cost scenario.

Figure 7-13 Cost of CO_2 savings versus Gas boiler: Base case (Typical semi-detached)



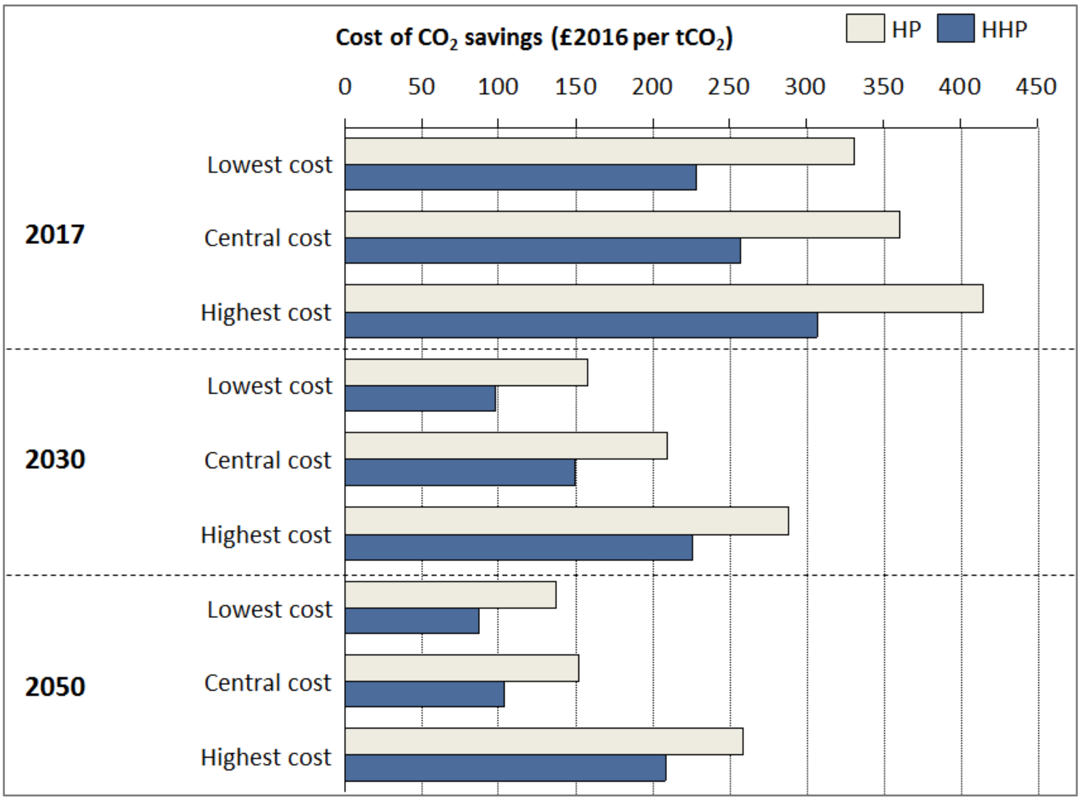
In the case of the HHP with the Smaller HP component (2 kW instead of 5 kW), as shown in Figure 7-14, the cost of CO_2 savings is slightly lower than in the Base case (the counterfactual HP is unchanged). The cost of CO_2 savings for the HHP reduces to £190/tCO_2 in 2017 for the central cost scenario, and to £65/tCO_2 in 2050 for the central cost scenario and £50/tCO_2 for the lowest cost scenario.

Figure 7-14 Cost of CO_2 savings versus Gas boiler: Smaller HP case for HHP



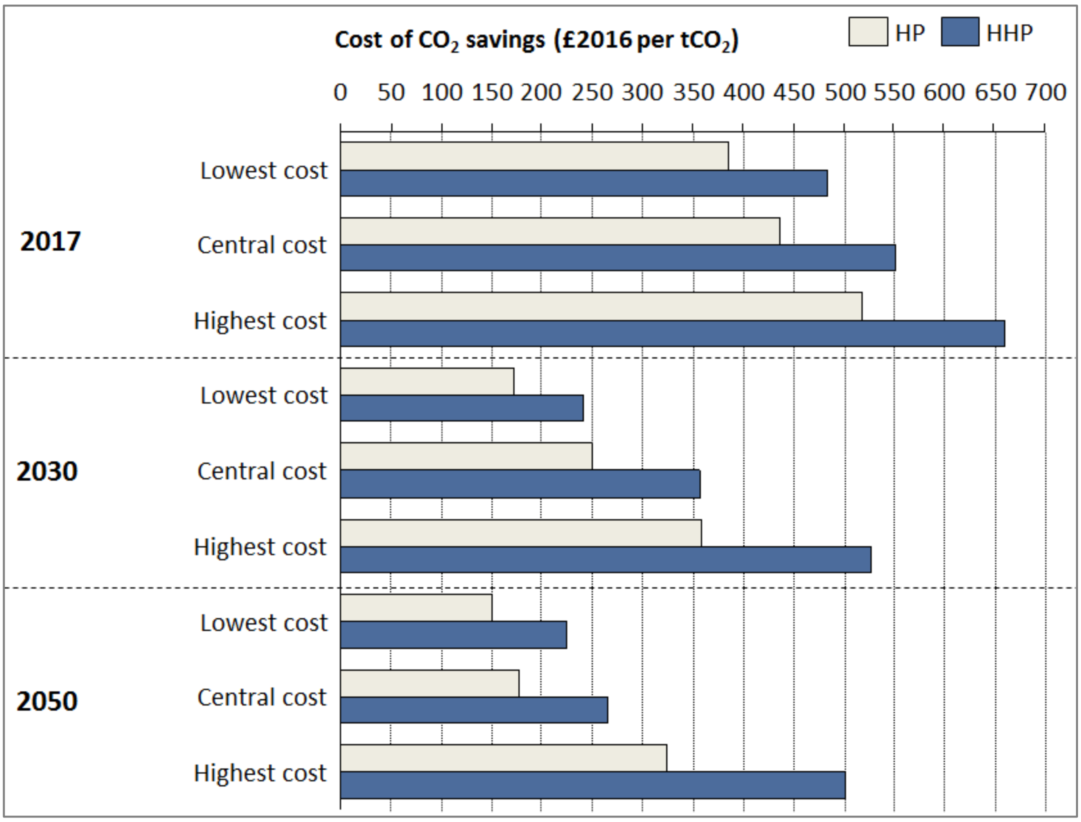
In the case where Low T emitters are applied to the HHP, the substantial increase in NPC and the modest increase in carbon savings (as presented above) mean that the cost of CO_2 savings are substantially higher than in the Base case. For installations in 2017, the cost of CO_2 savings is £260/tCO_2 for the central cost scenario compared with £215/tCO_2 in the Base case. The cost of CO_2 savings remains higher than in the Base case for all years and all cost scenarios. Nonetheless, the cost of CO_2 savings remains significantly lower in all cases for the HHP than for the HP.

Figure 7-15 Cost of CO_2 savings versus Gas boiler: Low T emitters case for HHP



For the Zero-carbon semi-detached building, the opposite trend is seen; as a result of the slightly higher NPC of the HHP versus the HP, combined with the higher carbon intensity of heating for the HHP, the cost of CO_2 savings is substantially higher for the HHP option than for the HP option. For installations in 2017, the cost of CO_2 savings in the central cost scenario is as high as £550/tCO_2 for the HHP option, compared with £440/tCO_2 for the HP option. By 2050, the cost of CO_2 savings in the central cost scenario falls to £265/tCO_2 for the HHP and £180/tCO_2 for the HP.

Figure 7-16 Cost of CO_2 savings versus Gas boiler: Zero-carbon Semi-detached with low T emitters



Overall, the analysis of the cost of CO_2 savings versus the Gas boiler case suggests that for typical existing buildings, HHPs offer substantially more cost-effective heat decarbonisation option than standard HPs. While the cost of CO_2 savings remains high in 2017, at around £200/tCO_2, the cost could fall to below £80/tCO_2 in an optimistic cost reduction scenario by 2030. Under the same cost reduction assumptions, the cost of CO_2 savings from the standard HP at the same point in time are expected to remain above £150/tCO_2.

In this case, the case for HHPs rather than HPs as the most appropriate option for heat decarbonisation rest on whether or not the level of carbon emissions reduction is sufficient. In the near term, the reduction in carbon emissions brought about by a switch from gas boiler to HHP is almost as large as for a switch to a standard HP, and the substantially greater cost-effectiveness provides a strong argument for the use of HHPs. In the longer term, however, it should be recognised that HHPs may not provide the extreme level of decarbonisation desired. This could in part be mitigated by use of the HP to provide DHW as well as space heating (although this would reduce the cost-effectiveness), and could also be addressed by reducing the carbon intensity of gas (e.g. through increased use of green gas).

The opposite trend in terms of cost-effectiveness, however, is observed for highly thermally efficient buildings, where cost savings can be achieved in the standard HP case since a smaller HP would be sufficient and the cost of replacement of emitters can be foregone. In this case, the HHP offers a less cost-effective alternative due to the additional cost of the boiler and controller. In this case, however, the cost of CO_2 savings remains high for both HHPs and HPs, since the greater thermal efficiency reduces the lifetime carbon savings; the cost of CO_2 savings remains above £150/tCO_2 even in 2050 in the most optimistic cost reduction scenario for the standard HP option.

8 Summary of findings

This report has presented findings on the current in-situ performance and costs of domestic HHP systems, and on how these characteristics might change as a result of market growth and innovation.

The study draws on a wide range of sources (including a review of existing literature and field trial data, consultation with industry stakeholders, and the results of dedicated technical modelling) to identify key opportunities where HHP systems could offer improvements over gas boilers and / or standalone heat pumps, in terms of the following factors:

- **Carbon emissions intensity** of heating (e.g. gCO_2/kWh);
- **Cost-effectiveness** (in terms of upfront capital cost and lifetime cost of heating i.e. net present cost);
- **Impact on the wider energy system** (in particular the **peak electricity** demand during the coldest days of the year, and demand flexibility);
- **Consumer acceptability** in terms of space requirements, noise, and other factors.

The main findings of the report can be separated into performance and cost related aspects, and they are summarised under these categories below.

8.1 Performance of HHPs

Performance of HHPs varies across different house types. Most of the results in this study are shown for a 'typical semi-detached house', and as such, the impacts of other parameters are discussed below in terms of their effects on HHP performance for this house type (unless otherwise specified).

8.1.1 Carbon emissions intensity

The **carbon emissions intensity** of heating attributed to a HHP system is influenced by several factors, the most material of these being:

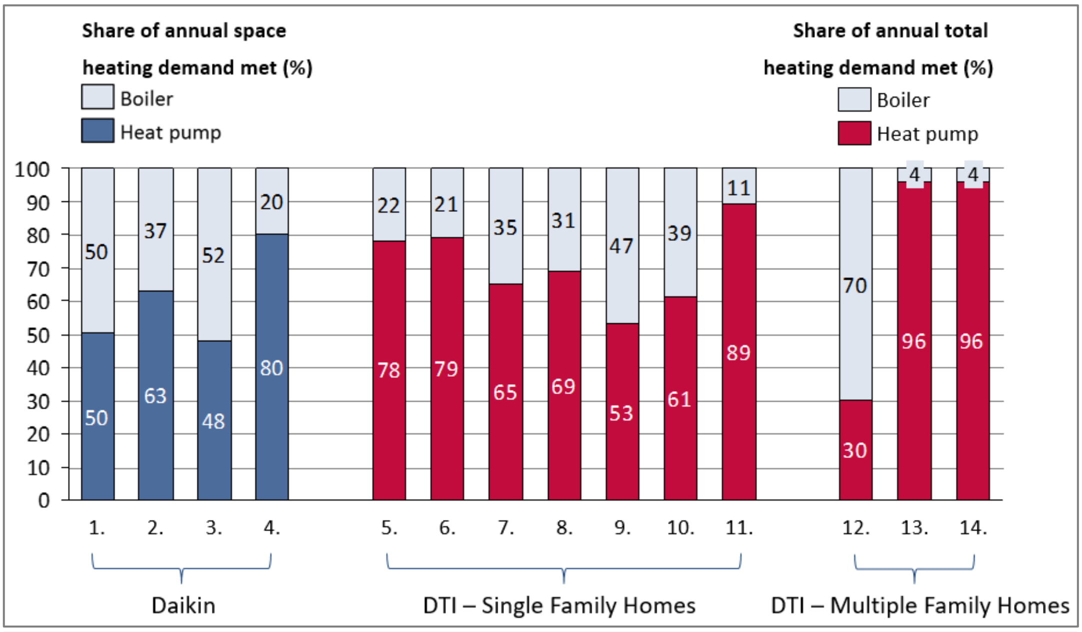
- capacity of the heat pump component, relative to the peak heating demand;
- heating schedule followed (e.g. continuous or twice a day heating);
- hybrid mode (i.e. switch or parallel) if a twice a day heating profile is followed
- mode of domestic hot water (DHW) heating.

Emissions intensity is also affected (to a lesser extent) by the type of emitters and the HHP control strategy.

The **capacity of the heat pump** in relation to the heating demand of a building ultimately determines how much heat can be provided using the heat pump, and how much must be provided by the gas boiler. Alongside the heat pump COP, this is fundamental to determining the potential emissions savings of a HHP. As such, the technical modelling aspect of this study considers a default case where the heat pump component of a hybrid system is sized to comfortably meet the entire space heating demand on an average winter day, when the HHP follows a continuous heating schedule. This ensures that the default case considers the maximum possible emissions savings (subject to the impacts of other operating conditions).

Observed data on the share of heat demand met by the HP component of HHPs suggests that in practice, this is highly variable. Figure 8-1 shows a selection of field trial results on the share of annual heat demand met by different components of a hybrid system, when installed in various house types with different levels of energy demand.

Figure 8-1 Observed share of annual heat demand met by heat pump and boiler components of hybrid systems

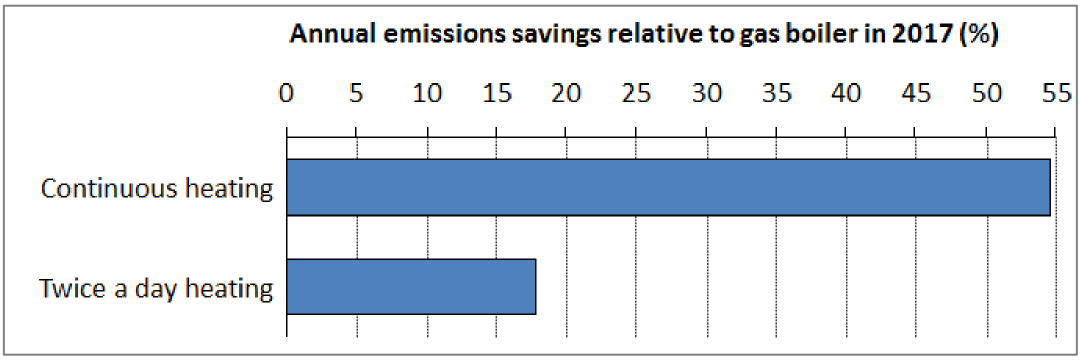


No.	Source	Monitoring period	Total heat production [kWh]	House type
1.	Daikin, 2017	July 2014 - March 2015	11,490	Two bedroom terraced house
2.		April 2014 - March 2015	3,452	Three bedroom semi detached bungalow
3.		May 2014 - March 2015	5,889	Three bedroom semi detached house
4.		May 2014 - March 2015	10,610	Three bedroom semi detached house
5.	DTI, 2015	October 2014 – September 2015	17,716	Single family home
6.			10,502	Single family home
7.			12,062	Single family home
8.			15,206	Single family home
9.			15,687	Single family home
10.			15,823	Single family home
11.			22,773	Single family home
12.			23,820	15 apartments, 936 m² heated
13.			87,850	18 apartments, 1099 m² heated
14.			84,670	19 apartments, 1151 m² heated

These results show that the share of heat met by a heat pump component of a hybrid system can be as low as 30%, or as high as 96%, with various values in between. The percentages shown for the Daikin trial only include space heating, while the hot water demand is met by the boiler, so the overall share of heat demand met by the heat pump will be lower than the results shown. The variation in the results suggests that house type, which impacts the total heat demand of a building, is likely to be a factor influencing the heat pump share of the annual demand and thus the emissions savings.

Heating schedule can also drastically alter the share of demand met by the heat pump component, and could account for some of the variation seen in Figure 8-1. A twice a day heating profile has high peaks in heat demand which require high flow temperatures, and must therefore be met by the boiler instead of the heat pump. This reduces the emissions savings of the HHP relative to a gas boiler. For example, Figure 8-2 shows that the annual emissions savings that could be achieved by a HHP installed in 2017 would be 55% under a continuous heating schedule, but only 18% for a twice a day heating schedule.

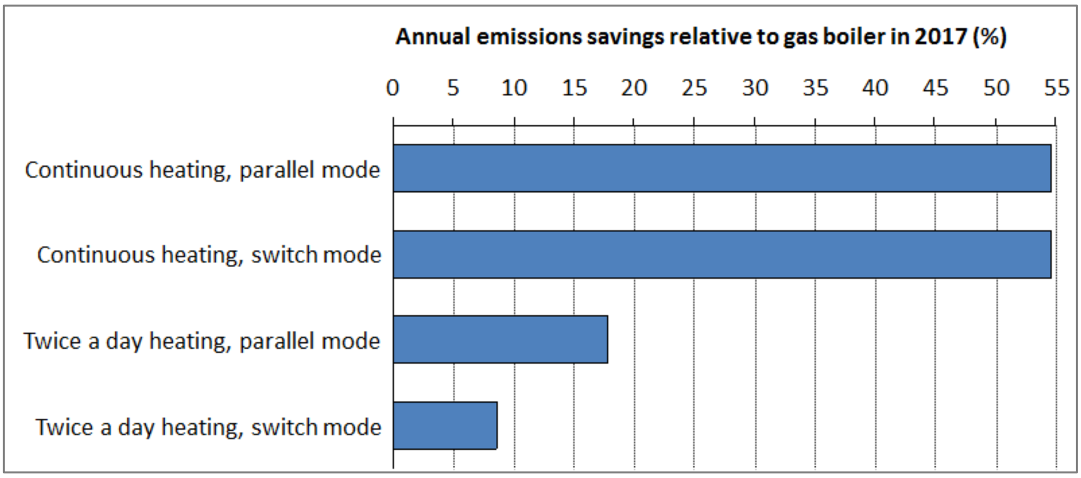
Figure 8-2 Impact of heating schedule on carbon emissions for a HHP in a typical semi-detached house



For some operating conditions, using a **switch hybrid mode** (where the entire heat demand for a certain period is met by the boiler if the HP component cannot meet the demand in that period) rather than a parallel hybrid mode (assumed to be the base case for HHPs, where the HP can contribute some heat during that period) can significantly reduce the emissions savings achieved. This is most likely to be the case for a system operating on a twice a day heating schedule, when the maximum output temperature of the HP can be a limiting factor (an effect which is exacerbated when the house does not have low T emitters installed, which is assumed to be the case for many HHPs).

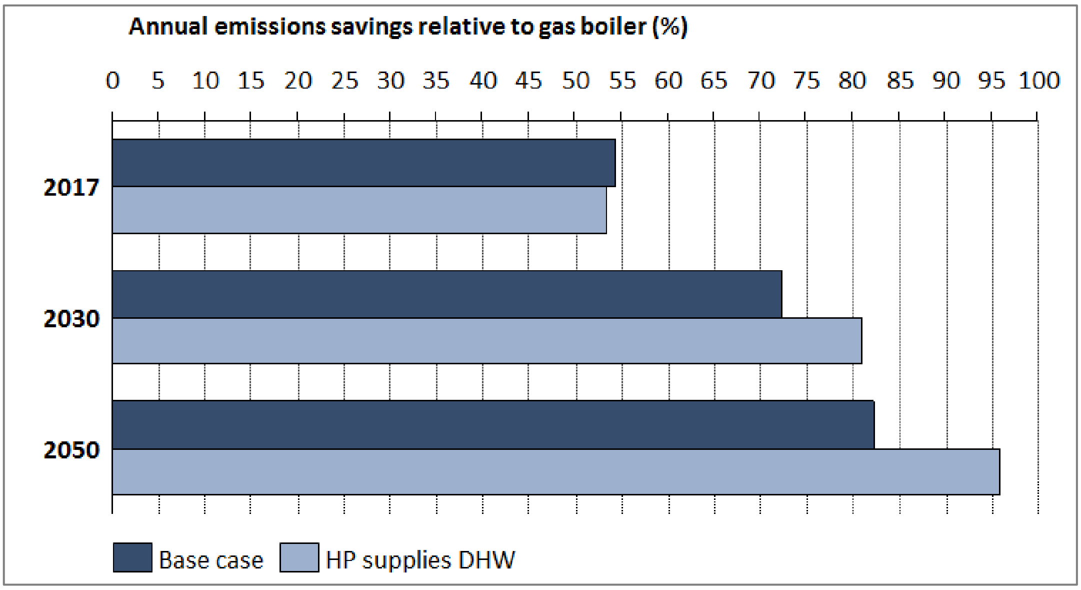
Figure 8-3 shows the impacts of operating in a switch mode on the annual emissions savings in 2017, compared to operating in parallel mode, for a HHP in a typical semi-detached house with high T emitters. In the twice a day heating case, using the switch mode leads to the emissions savings dropping to 9% (compared to 18% in parallel mode). However, using switch mode has no impact on the emissions savings for continuous heating. In this case, the flow temperature requirements for space heating are within the capabilities of the HP, so it can meet the whole demand in each time period, meaning that there is no difference between switch and parallel operation. Note that the boiler is assumed to meet the entire DHW demand in both cases.

Figure 8-3 Impact of hybrid mode on carbon emissions for a HHP in a typical semi-detached house (high T emitters)



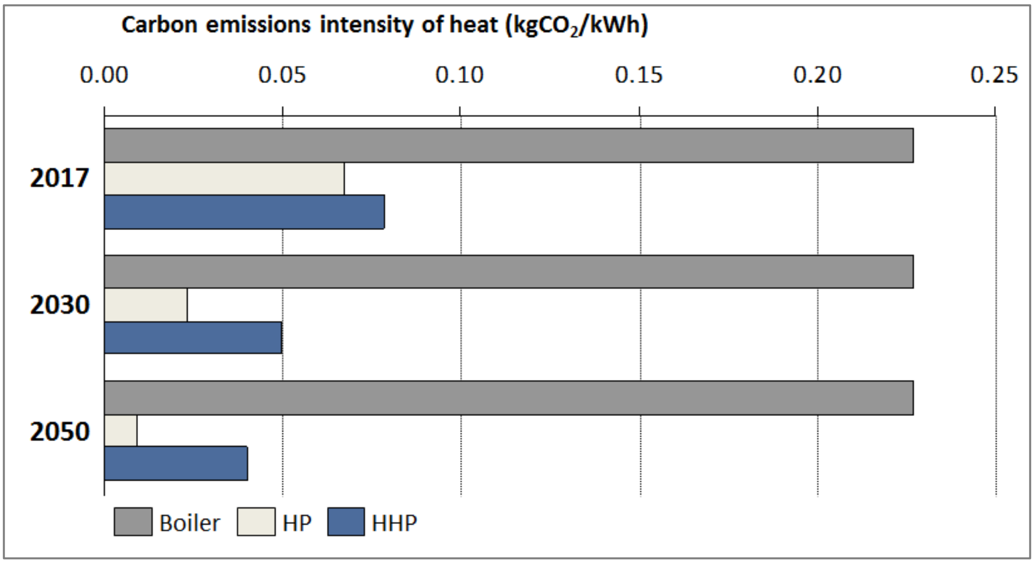
The mode of **domestic hot water heating** also impacts the carbon emissions intensity, due to the effect on the overall share of demand met by the heat pump component. For a HHP with a sufficiently sized heat pump, the share of heat demand met electrically could be maximised by generating DHW throughout the day using the heat pump (instead of the boiler component) and using thermal storage to store the heat until required. Due to the relatively low efficiency of the heat pump at the higher levels of demand for this case (and consequently higher flow temperatures), emissions savings compared to the base case would only be realised once further decarbonisation of the electricity grid has been achieved. The effect of decarbonisation on the two modes is shown in Figure 8-4.

Figure 8-4 Impact of DHW provision on carbon emissions from a HHP in a typical semi-detached house – shown for first year of operation only



For some building types, including the 'typical semi-detached' case, HHPs can currently achieve emissions savings (relative to gas boiler heating) which are very similar to those achieved by standalone heat pumps. The projected carbon intensity for the different heating systems, taken over the lifetime of the system, is shown in Figure 8-5.

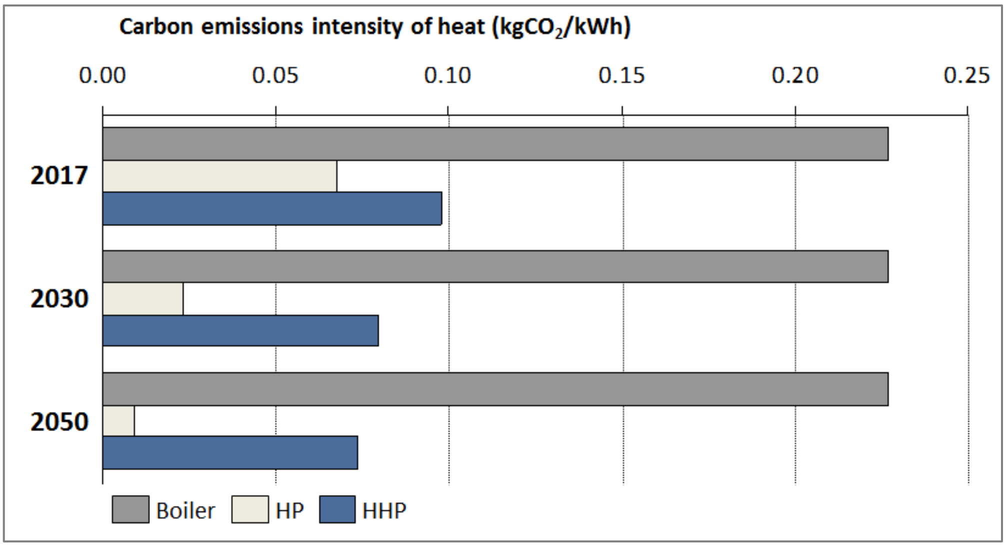
Figure 8-5 Projected carbon intensity of heat for HHP, HP and boiler heating systems (typical semi-detached, DHW met by the boiler component of HHP) – measured over 15 year lifetime



In the default case shown here, the savings compared to the boiler increase over time for the HHP and the HP, reflecting the decarbonisation of the electricity grid. However, this also means that over time, the emissions benefits of the standalone heat pump over that of the HHP also increase.

For very efficient buildings, the emissions savings of HHPs compared to standalone HPs are lower, even for systems installed in 2017. This is largely due to the higher share of the total heat demand coming from DHW (which is assumed to be met by the boiler in the default HHP system). The corresponding projected lifetime emissions values for a ‘zero carbon’ new build semi-detached are shown in Figure 8-6.

Figure 8-6 Projected carbon intensity of heat for HHP, HP and boiler heating systems (zero-carbon semi-detached with low T emitters, DHW met by the boiler component of HHP) – measured over 15 year lifetime



8.1.2 Peak electricity demand

The following parameters can significantly impact the **peak electricity demand** from a HHP system, as well as affecting the **maximum additional domestic electricity demand during the evening peak period**:

a) capacity of the heat pump component, relative to the heating demand;
b) mode of domestic hot water (DHW) heating;
c) type/sizing of emitters;
d) choice of hybrid mode (switch or parallel);
e) HHP control strategy.

The **capacity of the heat pump** in relation to the heating demand of a building determines how much heat can be provided electrically, and thus can provide an upper limit on the electricity demand from a hybrid system.

The effect of the mode of **domestic hot water heating** on the peak demand met by the heat pump component directly impacts the peak electricity demand; if the heat pump is used to provide DHW this can increase the peak electricity demand, compared to the case where the DHW is always provided by the boiler.

Using **low temperature (i.e. larger) emitters** can also reduce the peak electricity demand, compared to the default case where standard or 'high temperature' emitters are used. Heat pumps operate more efficiently at lower temperatures, and therefore for a given heat demand, the electricity demand from the heat pump component will be lower.

Using **switch hybrid mode** rather than a parallel hybrid mode may result in a lower peak electricity demand for the twice a day heating schedule; in this case, if the HP component cannot meet the whole peak demand, the boiler meets the entire demand at this time.

Figure 8-7 and Figure 8-8 show the impacts of the parameters described above on the peak electricity demand of a HHP in a typical year, and on the maximum additional electricity demand from HHPs observed in the evening peak period. Values are also shown for the equivalent cases for a standalone HP.

Figure 8-7 Peak electricity demand for HHP and HP systems in typical semi-detached (assumes electric resistive backup in the standalone HP case)

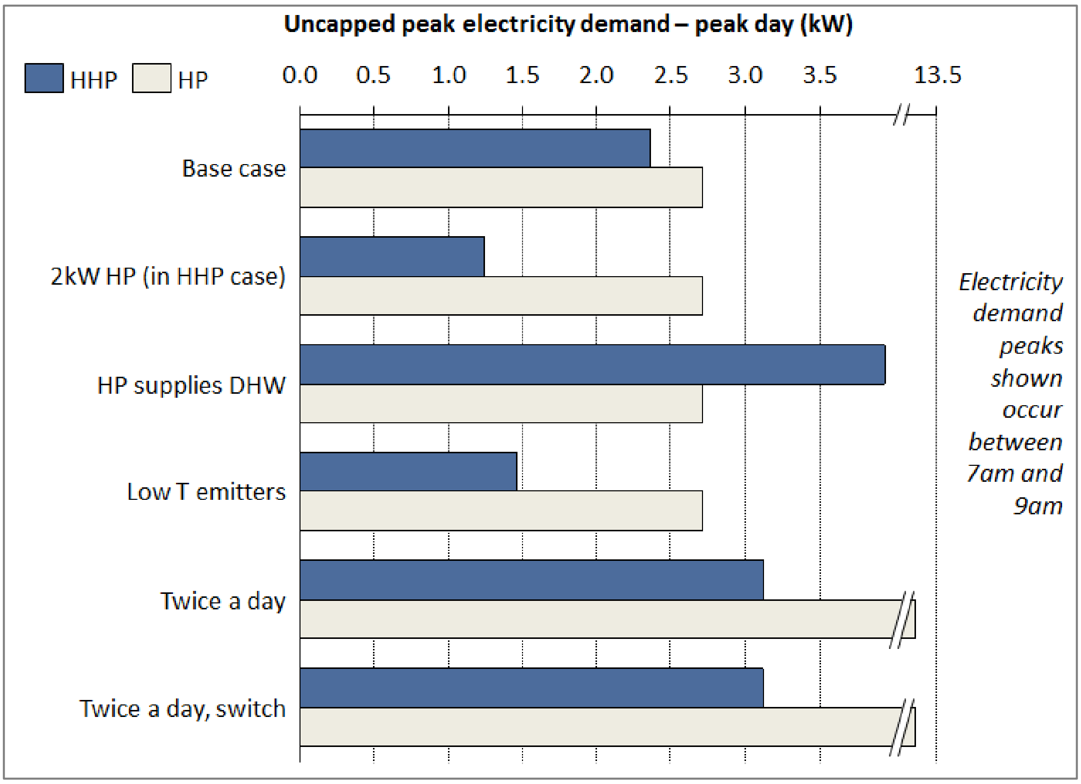
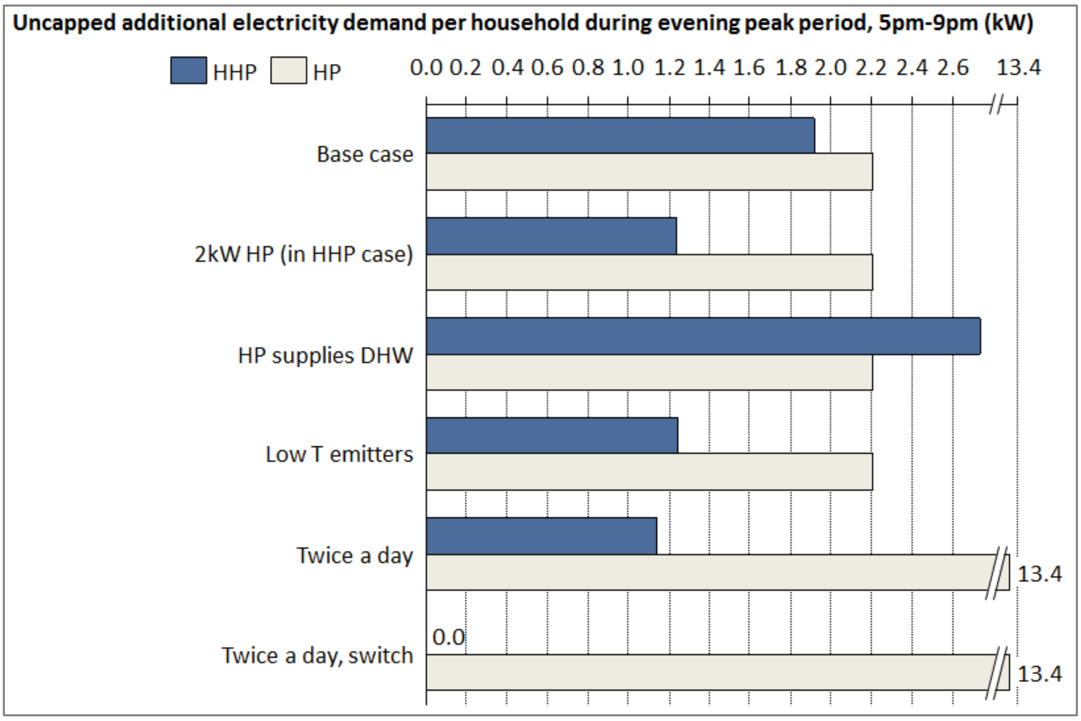


Figure 8-8 Additional electricity demand during evening peak period, for HHP and HP systems in typical semi-detached (assumes electric resistive backup in the standalone HP case)

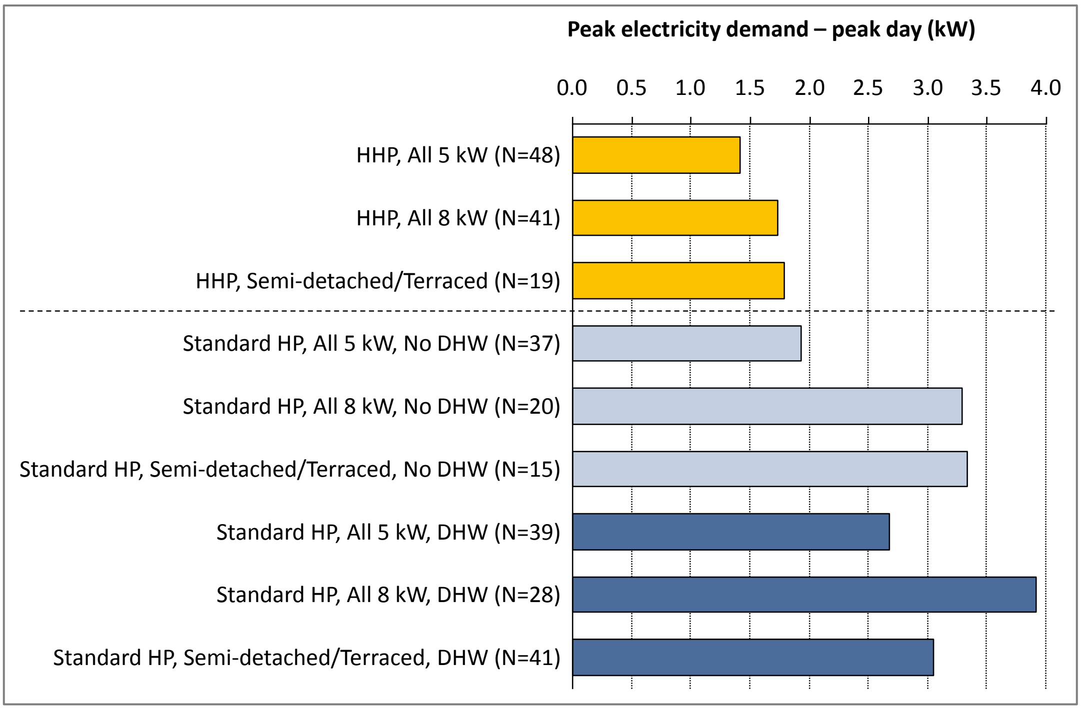


As well as showing how the peak electricity demand is affected by the different parameters, the values in Figure 8-7 and Figure 8-8 illustrate the general finding that

HHPs have the potential to significantly reduce the peak electricity demand compared to a standalone HP. The only case for which this is not necessarily true is the case where the DHW demand is met by the heat pump component of a HHP system. In this case, at the time of peak demand, the heat pump provides space heating as well as filling the DHW store[36]. The efficiency of the heat pump will be lower in the HHP case due to the use of High T emitters, compared to Low T emitters in the standalone HP case. This leads to a higher peak in electricity demand in meeting the same level of heat demand.

The modelled peak electricity demand values are comparable to those observed in the Manchester heat pump field trial. Figure 8-9 shows the peak electricity demand on the peak day for various system types in the field trial, shown separately for 5 kW systems, 8 kW systems and for systems of any size in Semi-detached or Terraced properties. As with the modelled data, the HHP systems show a significant reduction to peak electricity demand compared to the standalone HP systems.

Figure 8-9 Field trial results: peak electricity demand on the peak day, for various system types



Alongside the options for peak reduction shown in Figure 8-7 and Figure 8-8, various control strategies could be used within a hybrid system to fundamentally limit the conditions at which the heat pump works, thereby reducing the peak electricity demand. This could be as simple as adjusting the temperature set-point so that at times of peak demand (i.e. on colder days) the boiler takes over. More advanced ‘smart’ controllers could potentially enable the heat pump to switch off (or turn down, in a parallel hybrid mode) in response to grid signals at times of peak network loading, or in response to dynamic pricing. These strategies may reduce the overall emissions benefits of HHPs, even when the higher emissions of electricity generated during the evening peak period is taken into account, but nevertheless this capability is one of the main motivations for considering HHPs as an alternative to standalone heat pumps.

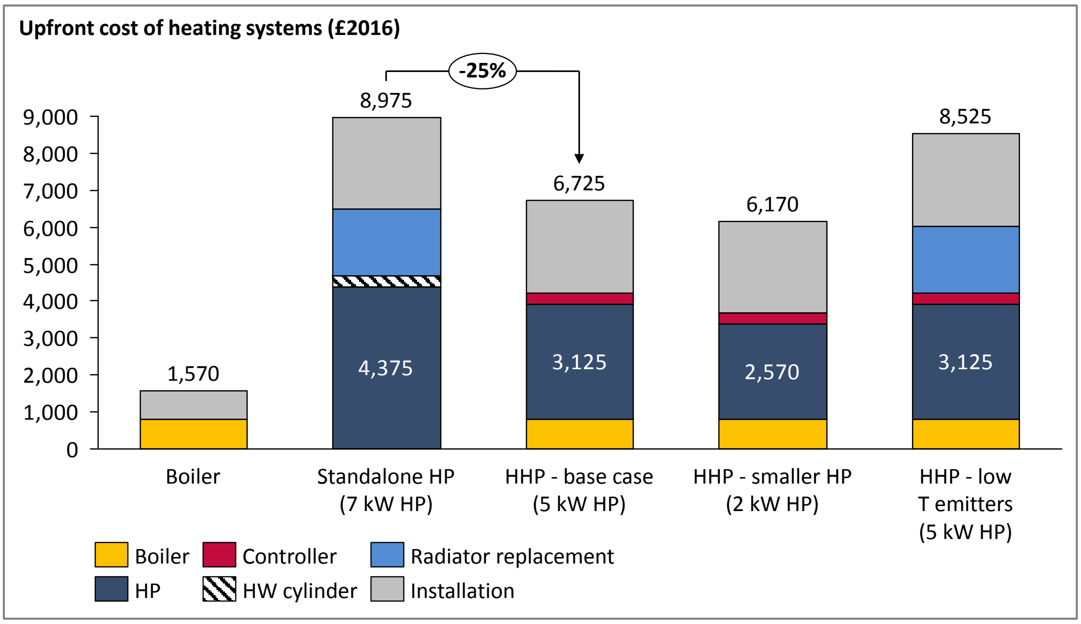
[36]While this assumes that the store is filled at times of lowest demand, for a continuous heating profile, DHW generation inevitably coincides with space heating.

8.2 Cost of HHPs

8.2.1 Upfront costs

As with the performance aspects, the cost of a HHP varies according to various system parameters. Figure 8-10 shows the breakdown of costs for a packaged HHP system in a few different configurations, compared to a standalone heat pump and a gas boiler, for a typical semi-detached house. Values shown are mean results from the range found in the literature and through the industry consultation.

Figure 8-10 Upfront costs of HHP, HP and boiler heating systems for a typical semi-detached (central cost case)

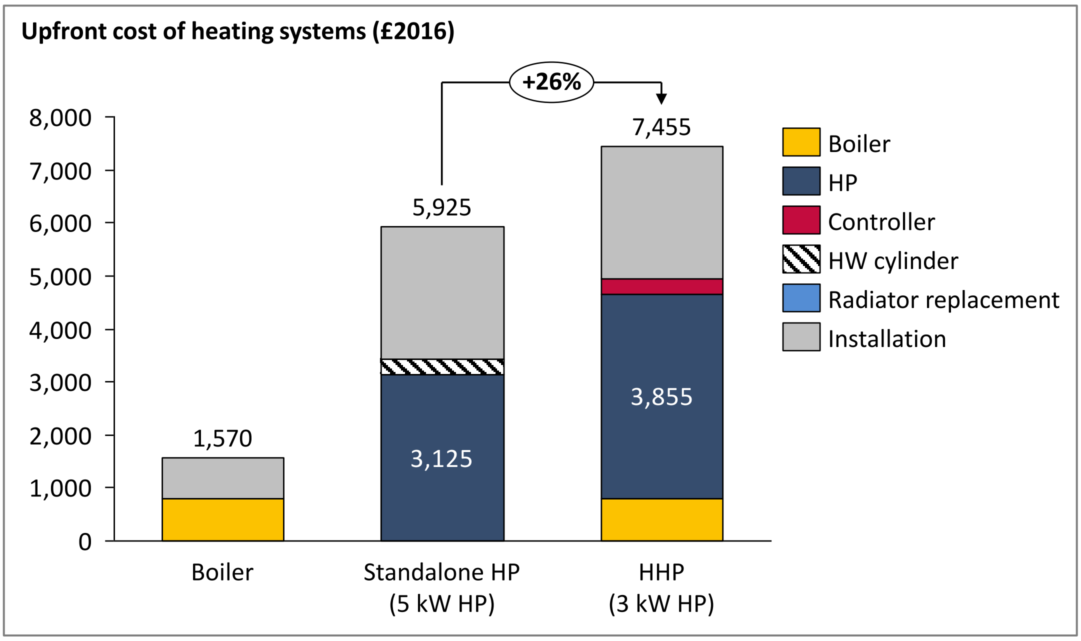


As shown in Figure 8-10, for a typical semi-detached house, HHPs and standalone HPs carry a cost premium of around £5,000-£7,500 over the gas boiler case. However, **HHPs currently offer upfront cost savings of £450-£2,800 compared to a standalone HP, for a typical semi-detached house**. Savings mainly result from the ability not to replace existing emitters (radiators) with low-temperature emitters in the HHP case, and also the ability to reduce the rated capacity of the heat pump component in the HHP case compared to the standalone HP case. Additional savings can be realised by choosing to provide DHW with a combi boiler, thus avoiding the cost of a hot water cylinder required for DHW generation by the heat pump.

It should be noted that in the case shown in Figure 8-10, the cost differential between the HP components of the HHP in the base case and the ‘smaller HP’ case is only £555, for a 2kW system versus a 5kW system. This is because cost per kW value used for heat pumps below 5kW capacity was significantly higher than the equivalent cost for heat pumps above 5kW. Although the two values are based on the available literature and industry consultation, there was only one data point for the smaller heat pumps. It is possible that in future, perhaps as a greater number of sub-5kW heat pumps enter the market, the cost of those smaller HPs could reduce further.

For highly efficient new builds, however, HHPs may not bring upfront cost savings over standalone HPs. For example, Figure 8-11 compares the capital costs for the different heating systems in a new build, ‘zero carbon standard’ semi-detached house.

Figure 8-11 Upfront costs of HHP, HP and boiler heating systems for a zero carbon semi-detached (central cost case)



Due to the lower space heating demand of this house type, it is assumed that the heat pump components in the HHP case and the HP case are smaller in size compared to those used in the typical semi-detached house (3kW and 5kW respectively, compared to 5kW and 7kW). Due to the higher price per kW of smaller systems assumed here based on the available data (see discussion above), this means that the heat pump cost is slightly higher for the HHP case than the standalone HP case. More significantly, it is assumed that this house type (new build) is fitted with low T emitters at the point of construction, meaning that the HHP case does not benefit from avoiding the costs of low T emitters. Taking into account the additional cost of the boiler and controller unit for the HHP, this makes the HHP case 26% more expensive than the HP case. This result should be treated with some caution, as the heat pump component costs are highly sensitive to the £/kW assumptions for systems below 5kW (for which data was very scarce). However, the avoided cost of emitter replacement in the HP case for highly thermally efficient buildings is the more important driver, and irrespective of the comparative HP cost, this will reduce the economic benefit of HHPs relative to HPs in those building types.

The literature review and stakeholder consultation revealed considerable uncertainty around future costs of HPs and HHPs, but broad agreement that there is scope for some level of cost reduction, both in product costs (mainly for the heat pump component) and notably in the installation costs. Three cost reduction scenarios were developed based on the information available, to capture the range of potential costs for HHPs going forward to 2050. These scenarios are shown for product costs and installation costs in Table 8-1 and Table 8-2 respectively.

Table 8-1 Summary of product cost reduction scenarios

Scenario	Product cost reduction compared with 2017 (%)			Description
	2030	2040	2050	
High	30%	30%	30%	Annual sales increase to the 100,000s, and this level sustained through the 2020s, leading to a 30% cost reduction by 2030
Central	17%	30%	30%	Annual sales increase to the 100,000s only by the late 2020s, leading to a 30% cost reduction by 2040
Low	0%	0%	0%	Little to no increase in annual sales versus 2017; alternatively, sales increase but improvements in product efficiency mean prices do not reduce significantly

Table 8-2 Summary of installation cost reduction scenarios

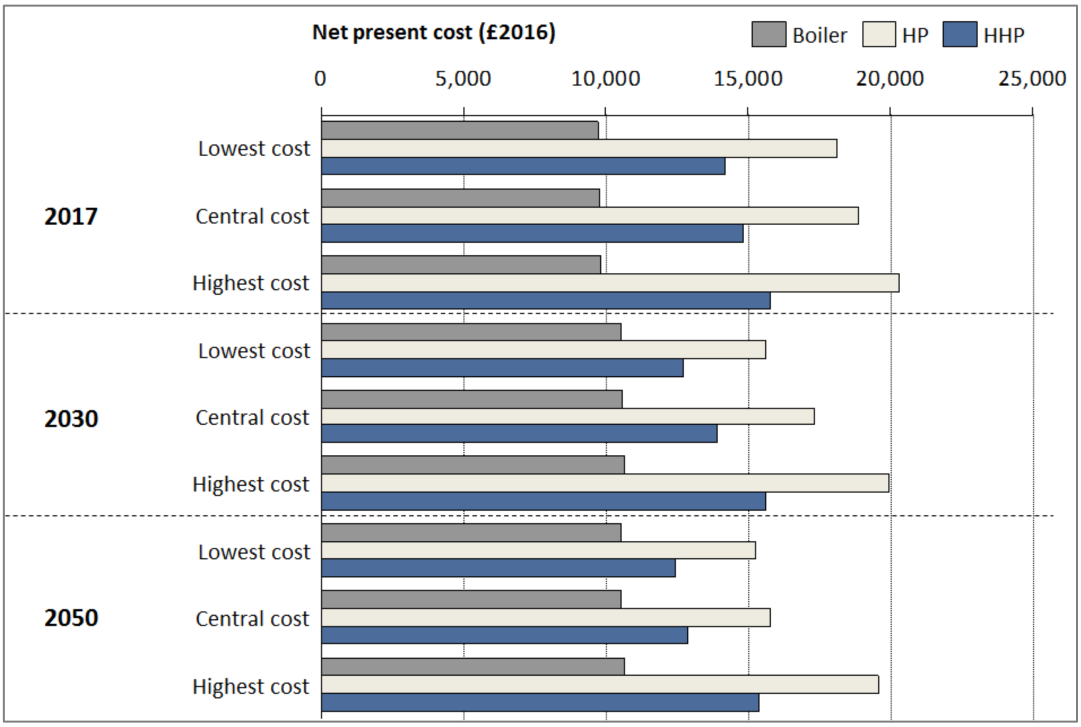
Scenario	Installation cost reduction compared with 2017 (%)			Description
	2030	2040	2050	
High	30%	30%	30%	Annual sales increase to the 100,000s, and this level sustained through the 2020s, leading to a 30% cost reduction by 2030
Central	17%	30%	30%	Annual sales increase to the 100,000s only by the late 2020s, leading to a 30% cost reduction by 2040
Low	10%	10%	10%	Little to no increase in annual sales versus 2017; small increase in competition leads to 10% cost reduction by 2030

8.3 Net present cost

Due to the significant upfront cost premium of HHPs and HPs versus the gas boiler counterfactual, the lifetime costs of those options substantially exceed those of the gas boiler option. However, HHPs can, for some building types, offer large lifetime cost savings over HPs.

For example, Figure 8-12 shows a comparison of the net present cost (NPC) of the HHP, standard HP and Gas boiler options, for installations in different years, for the central cost scenario (central values for current costs, and the central cost reduction case). For the typical semi-detached building, in 2017, the NPC of the gas boiler counterfactual is approximately £11,000. The NPC of the HHP is around £15,000 in the central case, which is significantly higher than the boiler case, but offers savings compared to the HP case, which is £19,000.

Figure 8-12 Net present cost comparison: base case for typical semi-detached. Assumes a 15 year lifetime and a 3.5% discount rate.



The lifetime savings of the HHP option versus the HP option for the typical semi-detached case are due both to the **upfront cost savings**, as discussed in the previous section, which are **in the region of £2,000** for the case considered here, and to a lower ongoing fuel cost.

The lower fuel cost for HHPs versus HPs is mainly due to the use of the gas boiler to provide the DHW demand in the HHP case, combined with the price premium of electrical heating versus gas heating. The electricity to gas price ratio over the period 2017 to 2050 ranges between approximately 4 and 5; since the typical SPF achieved by the HP is less than 3 in the winter months, gas heating remains lower in cost than electrical heating using the HP over the whole time period 2017-2050 and in all scenarios considered[37]. Since the DHW demand is met by the Gas boiler in the HHP case, and this corresponds to 15% of the total heating demand, this leads to substantial ongoing cost savings of more than £100 per year, resulting in **further lifetime cost savings in the region of £2,000** (discounted at 3.5%) compared to the HP case.

It should be noted that these cost savings do not include any valuation of the reduced peak electricity demand achieved by the HHP compared to the HP. This could bring further reductions on a lifetime cost basis relating, for example, to time-of-use tariffs (where the higher tariffs could be avoided by switching to the gas boiler) or peak period rebates. This is likely to be relevant in the medium term, when the value of peak electricity reduction could become significant.

For highly efficient buildings, HHPs are less likely to offer lifetime cost savings relative to HPs, due to the relatively low heat demand to be met, the reduced cost differential for the heat pump components of the two systems, and the additional cost of the boiler and the controller in the HHP case (shown in Figure 8-11).

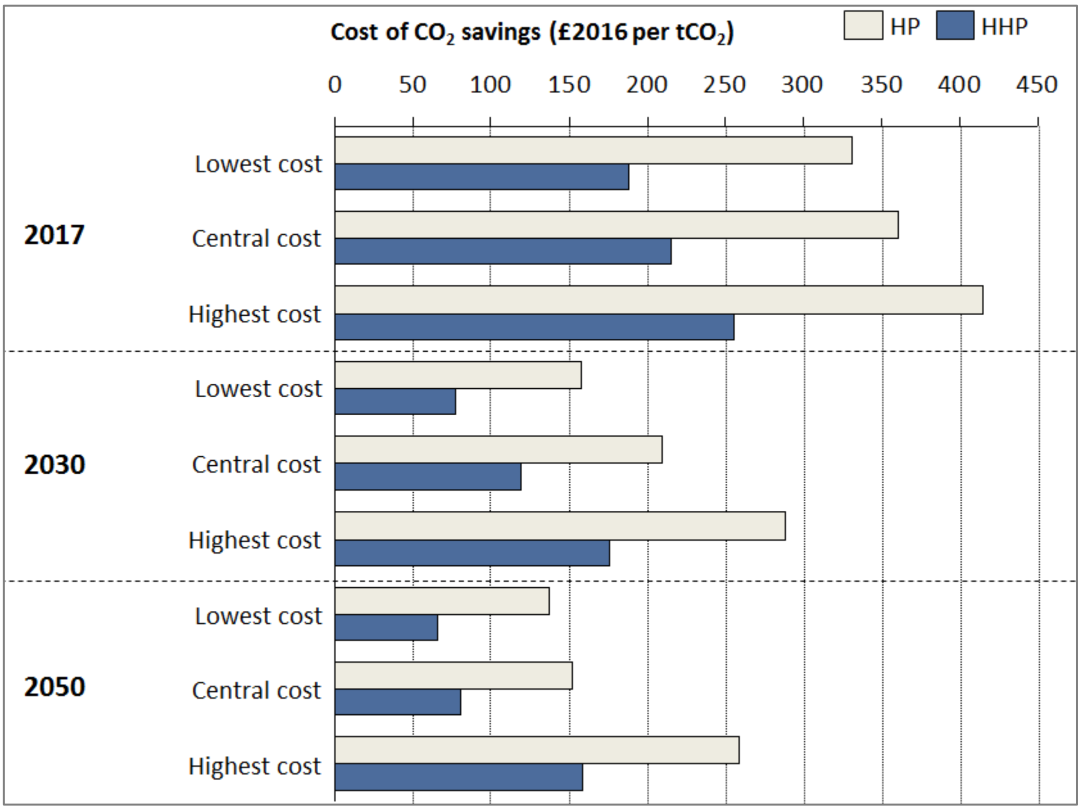
[37] Note that inclusion of carbon prices (not included here) could significantly alter the results particularly for installation in 2050.

8.4 Cost of emissions savings

This study derived scenarios for the **cost of carbon emissions savings** of the HHP and HP options versus the Gas boiler case by combining the evidence on lifetime net present cost with the evidence on the carbon intensity of heating.

Overall, the analysis suggests that for **typical existing buildings, HHPs offer substantially more cost-effective heat decarbonisation option than standard HPs**. This is shown in Figure 8-13, which presents the scenarios for the cost of CO_2 savings of HHPs and HPs relative to a gas boiler, for a typical semi-detached building.

Figure 8-13 Cost of CO_2 savings versus Gas boiler: Base case (Typical semi-detached, HHP uses existing emitters and DHW is met by boiler)

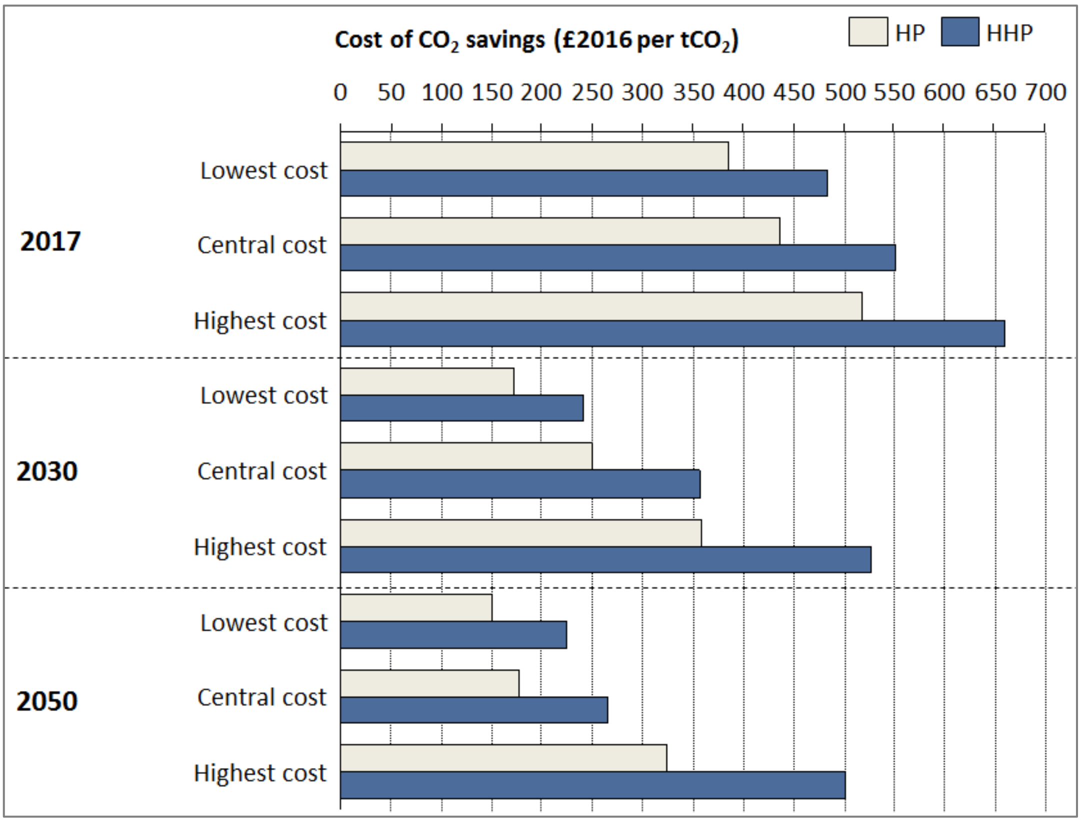


While the cost of CO_2 savings by HHPs remains high in 2017, at more than £100/tCO_2, the cost could fall to below £50/tCO_2 in the optimistic cost reduction scenario by 2030. Under the same cost reduction assumptions, the cost of CO_2 savings from the standard HP at the same point in time are expected to remain above £100/tCO_2.

In this case, the case for HHPs rather than HPs as the most appropriate option for heat decarbonisation rests on whether or not the level of carbon emissions reduction is sufficient. In the near term, the reduction in carbon emissions brought about by a switch from gas boiler to HHP is almost as large as for a switch to a standard HP (see Figure 8-5), and the substantially greater cost-effectiveness provides a strong argument for the use of HHPs. In the longer term, however, it should be recognised that HHPs may not provide the extreme level of decarbonisation desired (unless the carbon content of gas is significantly reduced over time).

In terms of cost-effectiveness, **the opposite trend is observed for highly thermally efficient buildings**, where cost savings can be achieved in the standard HP case since a smaller HP would be sufficient and the cost of replacement of emitters can be foregone. In this case, the HHP offers a less cost-effective alternative, due to the additional cost of the boiler and controller. This is shown in Figure 8-14.

Figure 8-14 Cost of CO_2 savings versus Gas boiler: Zero-carbon semi-detached with low T emitters



In this case, however, the cost of CO_2 savings remains high for both HHPs and HPs, since the greater thermal efficiency reduces the lifetime carbon savings; the cost of CO_2 savings remains above £100/tCO_2 even in 2050 in the most optimistic cost reduction scenario for the standard HP option.

9 Appendix

9.1 Manchester field trial data

As part of the Greater Manchester Smart Energy Project, 550 heat pump (HP) and HHP (HHP) systems were installed and monitored over some or all of the period from December 2015 to March 2017. Data was provided for 429 systems which had sufficient data for analysis. The trial includes a range of building types (flats, terraced, semi-detached, detached, bungalow) and building thermal efficiency levels. A range of HP and HHP system sizes are installed, from 4 kW_{th} to 8 kW_{th}. All HHP systems are 'integrated' HHPs manufactured by Daikin, and are either 5 kW_{th} or 8 $kW_{th.}$

The data collected is half-hourly, and includes:

- Date and time
- Heat pump power
- Total electricity power (i.e. total electricity demand for dwelling)
- External temperature
- Indicator of demand-side response (DSR) events applied during the trial

As shown in Figure 9-1 and Figure 9-2, data has been received for 89 HHP systems, 128 monobloc HP systems and 202 split HP systems. 10 installations are listed as type 'unknown', which are also of an unknown size.

Figure 9-1 Number of field trial installations by installation type

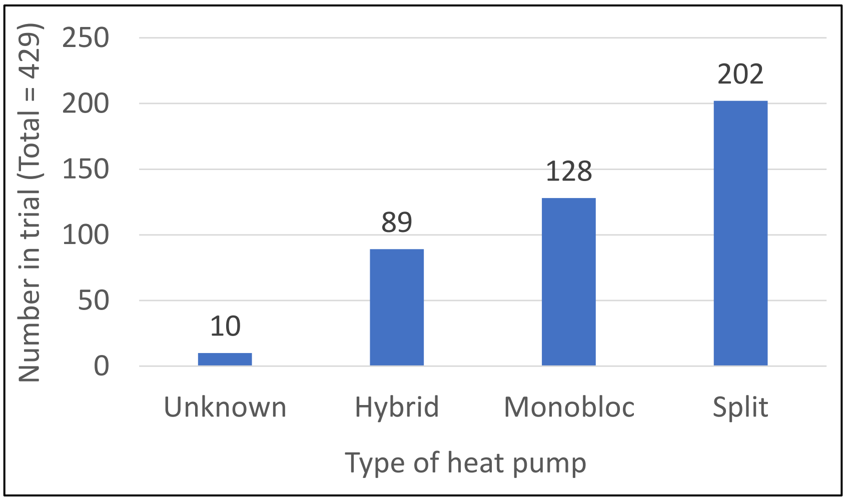
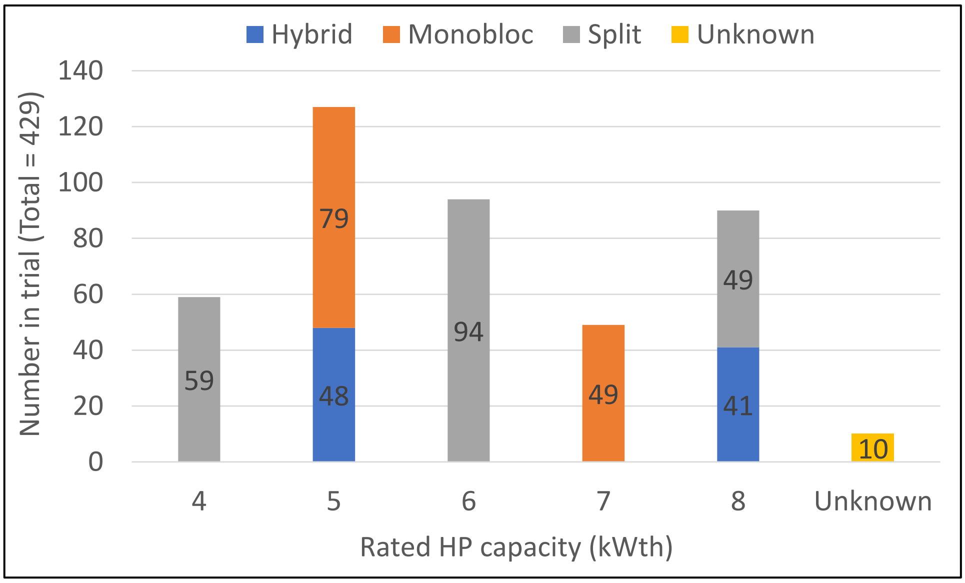
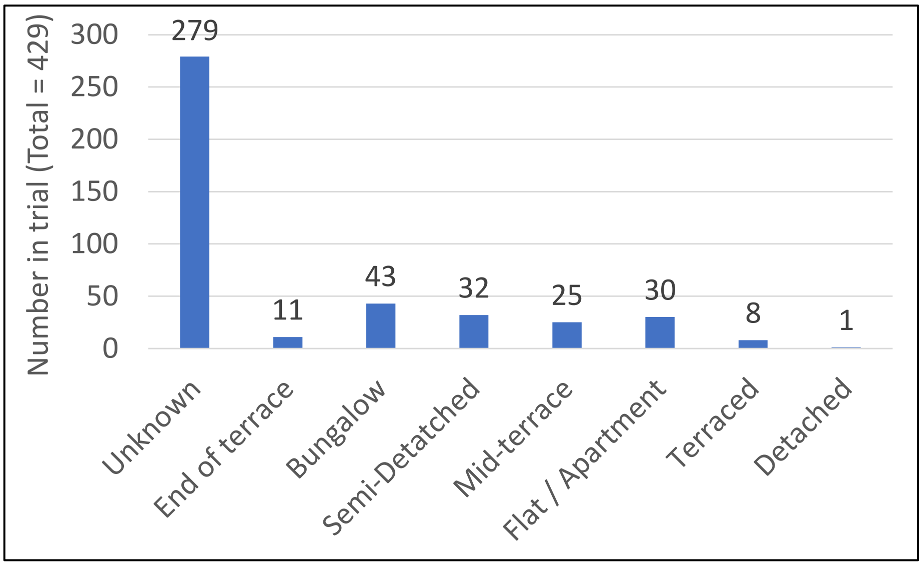


Figure 9-2 Number of field trial installations by installation size and type



Data on building type is incomplete; 279 of the HP or HHP systems are installed in an unknown building type. As shown in Figure 9-3, the installations for which building type is known include 44 terraced houses, 43 bungalows, 32 semi-detached houses, 30 flats and 1 detached house.

Figure 9-3 Number of field trial installations by building type



More than 200 installations have over 12 months' worth of monitoring data.

9.2 Heat demand profiles and heat pump performance modelling

Generating a twice a day heating profile

Heat pumps are not intended to be are used to achieve twice a day heating. If they are, the half hourly heat demand during operation can be very high, requiring high flow temperatures at which heat pumps operate inefficiently and may require a resistive heater to "top up" the heat pump output temperatures, leading to high levels of electricity demand. However, it is technically possible that heat pumps and hybrid heat pumps could be used in this way, and therefore this report has considered the possible impacts. The assumed heat demand profile for the modelling of these impacts is described below.

Diversified heat pump profiles from the CLNR heat pump trial[38] were used as the starting point to develop a twice a day heating profile for an individual heat pump. The following steps are carried out to transform these **diversified profiles** to a new twice a day **undiversified profile**:

1. The demand peak from overnight hot water generation (a pre-set programme for the heat pumps in this study) is removed. This results in a diversified profile with two peaks. For example, the profiles for January and February are shown in Figure 9-4. **Note this profile is shown in kWh per half hour. The corresponding February demand peak in kW would be 0.85 kWh / 0.5 = 1.7 kW.**

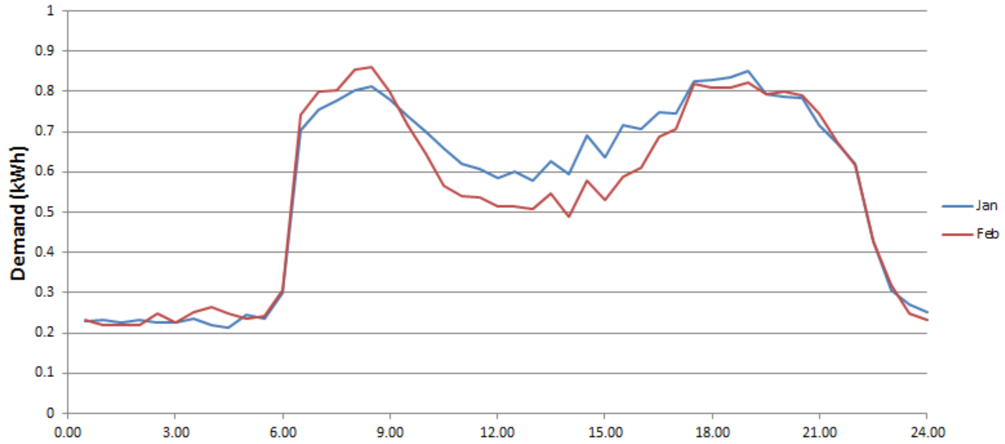


Figure 9-4 Diversified half hourly heat pump electricity demand during average January and February days (CLNR heat pump field trial data)

2. For each month, these diversified profiles are transformed into simple twice a day profiles with two peaks in demand (which are aligned with the timings of the diversified peaks), as follows:

   - The primary peak of the diversified profile in each month is multiplied by a factor of 2.4. This factor is calculated based on an approach developed for the CLNR trial analysis, and calculated explicitly for heat pumps using RHPP data in a UCL study; here, the diversified peak across all the RHPP sites (i.e. the After Diversity Maximum Demand) is 1.7kW (see bottom of p337 of that source)[39]. This also

[38] Durham Energy Institute and Element Energy, 2015. Customer-Led Network Revolution, *Insight Report: Domestic Heat Pumps*. Average monthly profiles shown on p12.
[39] Love J. et al (2017). *The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial.* Applied Energy Volume 204, 332-342.

matches the peak demand on an average February day for the CLNR profile above.

- Figure 8 in the same paper (p338) shows that the peak demand increases as the number of heat pumps included in the sample reduces towards unity; for one heat pump, the peak demand is 4 kW.
- The factor that should be applied to the peak to go from a diversified to undiversified profile is thereby calculated as 4/1.7 = **2.4.**

- The ratio between the primary and secondary peak in the diversified profile is preserved.
- The duration of the peaks in demand is selected to preserve the total electricity demand in each month, which is based on the share for each month seen in the CLNR data, then scaled down according to the ratio of estimated average annual heat demand between the buildings in the CLNR dataset, and the typical semi-detached building archetype used in our modelling.
- **The aim of this is to produce a profile with the level of peak demand observed in the real HP field trials, which can be seen to be approximately 4 kW, based on a diversified peak of 1.7 kW (from CLNR) multiplied by 2.4.**

3. The electricity demand profile for each month is then translated to a heat demand profile, using adjusted COP values from twice a day profiles generated using boiler heat demand (adjusted to slightly reduce the difference in performance between summer and winter months).

Figure 9-5 shows the resulting twice a day daily heat demand profiles for a typical semi-detached house on an average January day, a cold January day, and a 1-in-20 year cold January day. The minimum daily temperatures associated with these profiles are shown in the legend.

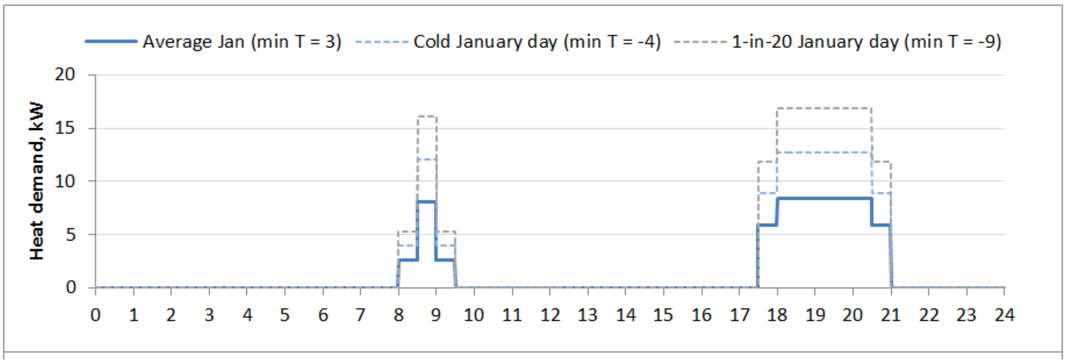


Figure 9-5 Twice a day heat demand profile for January days (typical semi-detached house)

Figure 9-5 shows how the peak heat demand on the average January day would be met by heat pumps of various rated capacities (it is assumed that a resistive heater is installed alongside the heat pump in each case). Modelled results are shown for a house with low temperature (low T) emitters and also for a house with high temperature emitters (high T)[40]. The results demonstrate the various impacts of different heat pump parameters:

a) In the "Low T emitters" case, the flow T required is below the maximum output temperature of the heat pump. In this case, **where the flow T required is not a limiting factor, increasing the nominal HP capacity enables the HP to meet the entire heat demand.** This also has the effect of improving the efficiency of the system over the peak period, as the HP will be more efficient than the resistive heater.
b) In the "High T emitters" case, the flow T required exceeds the maximum HP output temperature. The modelling assumes parallel operation of the HP and the resistive heater; the HP can contribute useful heat up to the maximum output temperature, and the resistive heater meets the rest of the heat demand. In this case, **where flow T exceeds the maximum HP output T, the share of the demand that can be met by the HP is limited; increasing the nominal HP capacity will not enable the HP to meet the entire heat demand.** This will reduce the overall system efficiency, and is more likely to occur with high T emitters than with low T emitters.

Figure 9-6 How peak heat demand in a typical semi-detached house on an average January day is met by heat pumps with various rated capacities (twice a day heating) (assumes electric resistive backup in the standalone HP case)

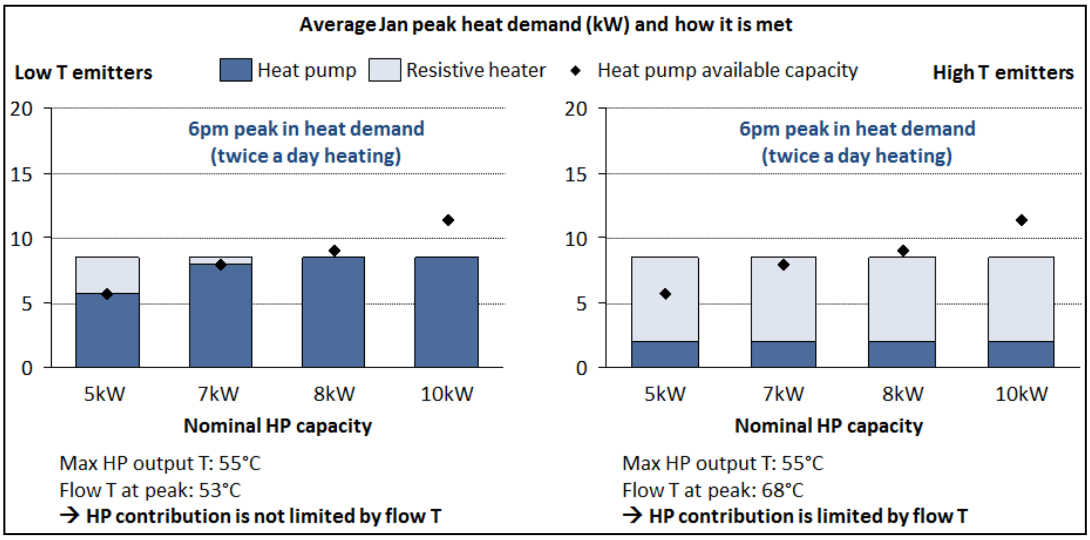


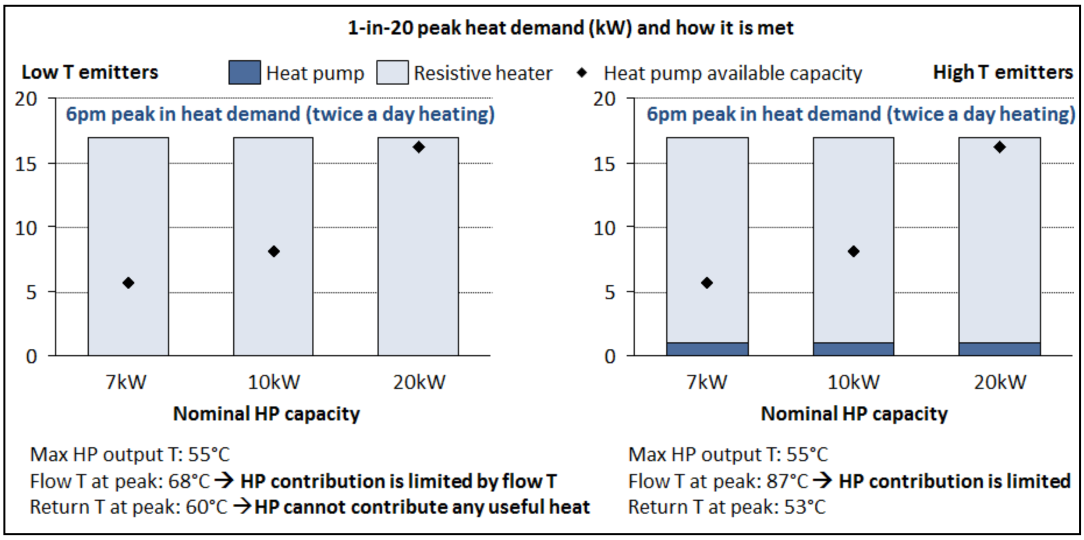
Figure 9-7 shows the same comparison for the peak heat demand in a twice a day heating schedule on a 1-in-20 year cold day (minimum temperature -9°C). In both the Low T and the High T emitter cases, the flow T required considerably exceeds the maximum HP output T, and increasing the nominal HP capacity does not enable the HP to meet the entire heat demand. However, in the Low T case, the return T also exceeds the maximum HP output T, and therefore the HP cannot contribute any useful heat[41]. In both cases, the

[40] Low T emitters: Flow temperature of around 45 degrees. Design temperature taken as 40/30 flow/return. High T emitters: Water to air temperature difference of 50-60 degrees, translating to a flow temperature of above 60 degrees. Design temperature taken as 80/60 flow/return.

[41] Domestic systems tend to have fixed flow rates. With low T emitters, to achieve the same peak heat output with lower flow temperatures compared to the high T emitter case, a greater volume of water must pass through the system in the same time period (i.e. a higher flow rate). This is due to the fact that the **energy transferred per kg of water passing through the system is lower in the low T case** (since the temperature difference with the air is lower). This also means that the delta T between the system flow

high level of heat demand combined with the high proportion of demand met by the resistive heater will lead to a high level of electricity demand occurring during the evening peak.

Figure 9-7 How peak heat demand in a typical semi-detached house on a 1-in-20 year coldest day is met by heat pumps with various rated capacities (twice a day heating) (assumes electric resistive backup in the standalone HP case)



This can be contrasted with the continuous heating case, where the heat demand is maintained at a low level throughout the day.

Modelling the electricity demand impacts of using a heat pump in a twice a day mode

Figure 9-8 shows the modelled total electricity demand from the heating system at peak times (i.e. between 5pm and 9pm) in a typical semi-detached house under a twice a day profile and a continuous heating profile. The results are shown for a 7kW rated HP and an 8kW rated HP, for a 1-in-20 peak day and an average January day.

The electricity demand figures shown are uncapped i.e. the modelling assumes that the system can draw as much power as it requires to meet the heat demand in each half-hourly period. For the twice a day heating schedule, on the 1-in-20 peak day this results in an electricity demand of 17.8kW (on top of the underlying evening household electricity demand), compared to 3.5kW in the continuous case (depending on the nominal HP capacity). However, such high levels of demand would exceed domestic power limits. In reality, if a twice a day heating schedule was applied on exceptionally cold days, this would lead to a number of possible outcomes:

a) The system would draw the maximum demand possible (likely to result in a significant increase in the per-household electricity demand), and the deficit would result in a loss in comfort if the target temperature is not achieved;
b) Depending on the system settings, the heat pump could turn on earlier to achieve the required temperature by a specified time.

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and return temperatures will be lower for a low temperature system than for a high temperature system.

Both of these outcomes would nevertheless cause a much greater increase in per-household electricity demand than the continuous heating case. Similarly, even on the average January day, the twice a day schedule would result in an additional demand of around 4kW during the evening peak, compared to 1.2kW for the continuous heating case.

Figure 9-8 Maximum uncapped additional peak electricity demand for different heat pump sizes and heating schedules in a typical semi-detached with low T emitters (assumes electric resistive backup in the standalone HP case)

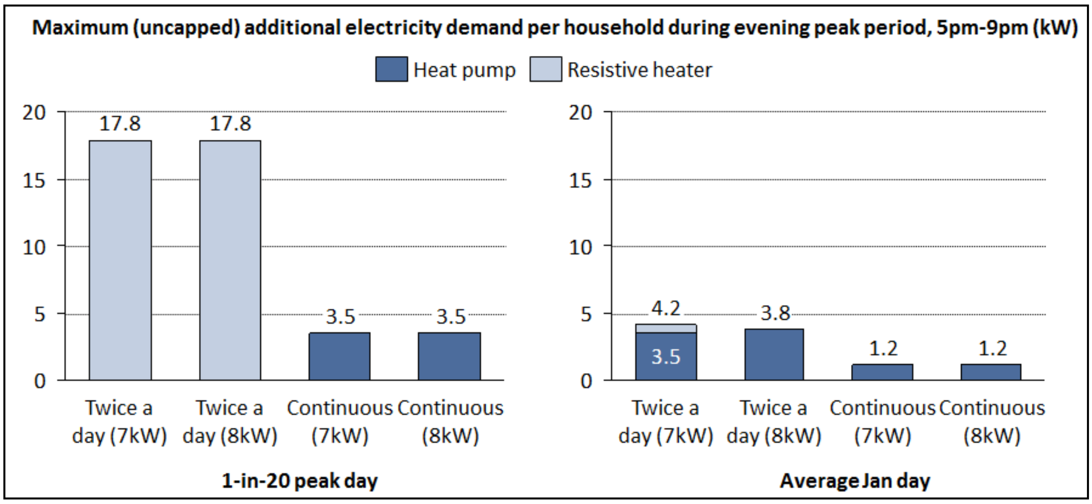
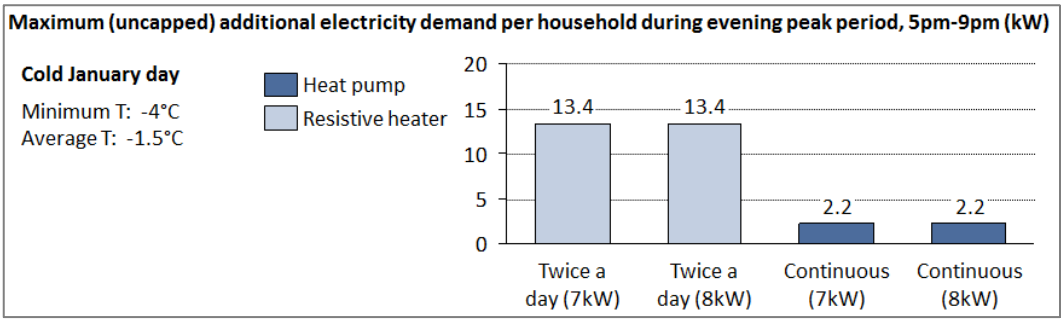


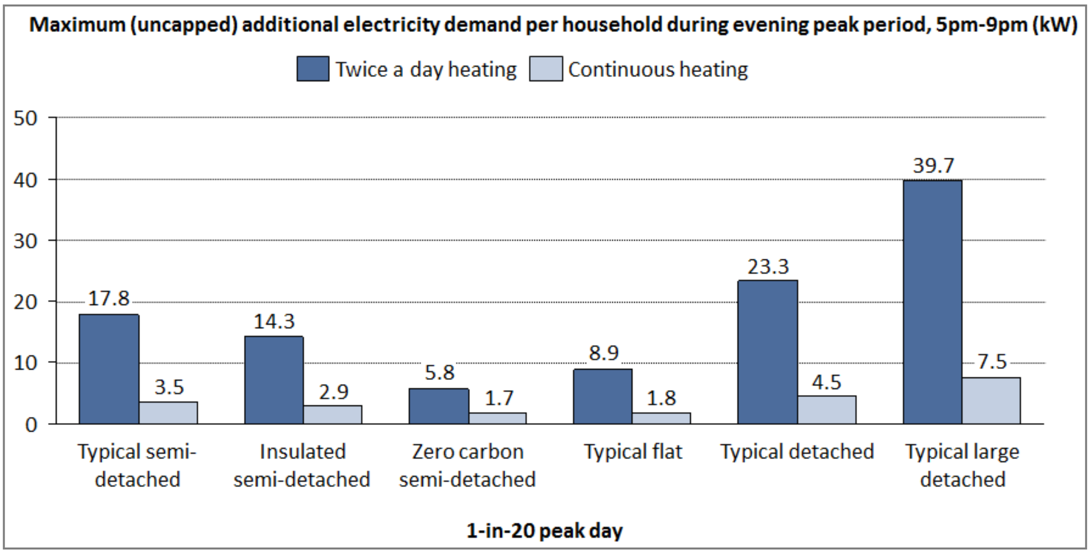
Figure 9-9 shows the equivalent modelled total electricity demand from the heating system at peak times on the coldest winter day in a typical year.

Figure 9-9 Uncapped additional peak electricity demand for different heat pump sizes and heating schedules in a typical semi-detached with low T emitters, on a cold January day (assumes electric resistive backup in the standalone HP case)



In comparing the calculated impacts of these two modelled heating schedules (shown for a "typical semi-detached" house), it must be emphasised that data collected in HP trials has revealed considerable variation in individual HP electricity demand profiles. While the "twice a day" profile was derived from observed monthly average HP demand profiles, differing user behaviour means that even for houses with similar energy efficiency characteristics, the evening peak electricity demand for a HP on an average winter day could be significantly higher than 4kW, as well as, in some cases, being as low as in the "continuous" heating schedule. In addition to this, the per-household "additional peak demand" varies with the energy efficiency and size of the building; Figure 9-10 shows the modelled results for different building archetypes in the twice a day and continuous heating schedules.

Figure 9-10 Maximum uncapped additional peak electricity demand for different heat pump sizes and heating schedules in a typical semi-detached with low T emitters, on a 1-in-20 year coldest day (assumes electric resistive backup in the standalone HP case)



As shown in Figure 9-10, even with a continuous heating profile, the peak electricity demand from heat pumps could range from 1.7 kW in a new build, zero carbon semi-detached, to 7.5 kW in a large detached house. Heat pump sizing assumptions are based on maximising the share of the heat demand which can be met without using the resistive heater (within the limits of the flow temperature requirements).

9.3 Heat pump performance modelling approach

The objective of this section is to describe the methodology followed in modelling the operation of hybrid heat pumps for typical residential applications. The modelling takes account of the following factors:

- Outside air temperature
- Heating requirements of the dwelling
- Heat pump output capacity and efficiency
- Boiler capacity and efficiency
- Heating system capacity (i.e. radiator heat transfer capacity)
- LTHW flow and return temperatures
- LTHW volume flowrate
- Hours of operation for the heating system (i.e. continuous or in-continuous)
- Hybrid control strategy (i.e. parallel or switch-mode)

The factors listed above vary in the degree to which they are external to the design and operation of the system. The most exogenous of these factors is the outside air temperature, which determines the heat load (for a given dwelling heating characteristic) and also affects the heat output and efficiency of the heat pump.

During the system design phase, the heat pump capacity can be chosen to match the forecast heat load. The heat pump efficiency can be improved to a degree by higher specification during design, by using larger, more efficient compressors and motors, variable speed drives, and larger heat exchangers (offering greater heat transfer capacities and so reducing temperature differences).

Once installed, the heat pump capacity is capped by the component capacities (e.g. compressor volume and speed) and the need for defrosting at low outside air temperatures.

We assume that the gas-fired boiler is sized to meet the full system heating capacity – in order to provide both top-up heating and to meet the full heating load during very low temperatures (when the heat pump may not operate). We assume for this analysis that the boiler efficiency is a constant (81% gross efficiency).

The heating system comprises of the heat emitters and associated heating hot water distribution system. For dwellings with older, conventional heating systems, we assume that these are radiators with sufficient heat transfer capacity to provide the rated heat output when served by LTHW with a flow temperature of 80°C and return of 60°C. Assuming the room air temperature is 20°C, this gives a conventional “delta T” of 50 degrees. For dwellings with energy efficient systems, we assume the use of low-temperature emitters (e.g. under-floor heating or high-efficiency radiators), served by LTHW with a flow temperature of 40°C and return of 30°C.

The LTHW flowrate is assumed fixed, at a level to meet the rated demand with a 20 degrees temperature difference between flow and return.

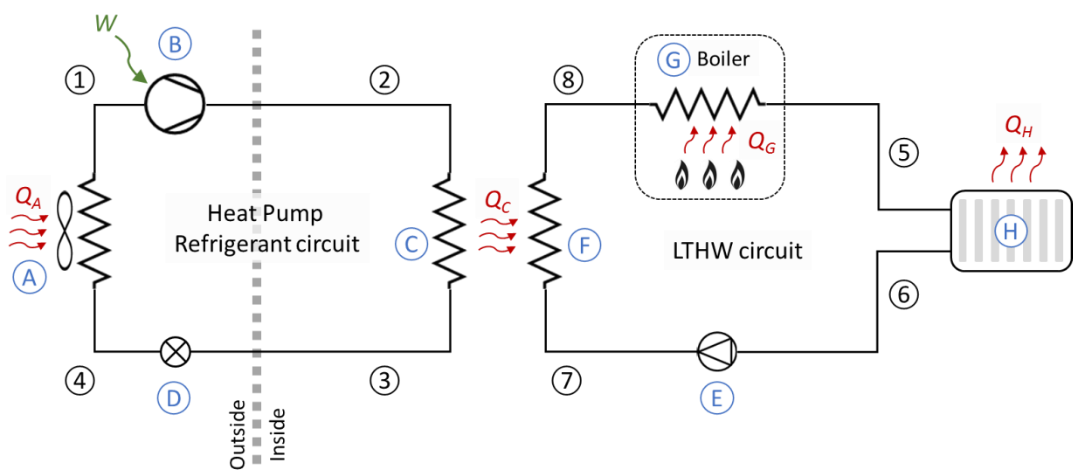
The hours of operation of the heating system has a significant impact on the peak heat demand placed on the system. If the system operates continuously, then it is assumed that the load profile on the heating system is the same as the heat loss profile of the dwelling (as a function of the outside air temperature). If the system is switched off for certain periods of the day (as is assumed normal in dwellings with conventional, gas-fired heating systems), then the internal temperature is allowed to drop below the set temperature (e.g. during the night), but then has to be brought back up to the set level when the system is switched on. This changes the heating load profile, which is no longer the same as the heat-loss profile, and introduces significant peak loads during the initial "warm-up" period.

The hybrid heat pump controls can be set to share the load between the heat pump and / or the boiler in different ways. In particular, at low external temperatures, and high contemporaneous high heat loads, it is assumed that the heat pump cannot meet the full heat load. Under these conditions, the controller may switch entirely to boiler mode with no heat pump output (called the "switch mode"); or a more advanced control system may continue to operate the heat pump (albeit with reduced output capacity) and provide top-up capacity with the boiler (the "parallel mode"). In the future, industry stakeholders suggested that further advances in control mechanisms could provide improvements in total system efficiency.

9.3.1 Methodology

The heat pump analysis uses a numerical model to estimate the heat output and efficiency of hybrid heat pumps at a range of heat loads, outside air temperature and LTHW temperatures. The model simulates the operation of a heating system, comprising of a heat pump circuit, connected in series with a gas-fired boiler, serving a simple LTHW heating system. This is illustrated in the heat flow diagram below.

Figure 9-11 Simple hybrid heat pump schematic diagram



KEY – REFRIGERANT CIRCUIT

COMPONENTS		SYSTEM OPERATING POINTS	
A	Evaporator fan-coil unit	1	Evaporator outlet
B	Compressor	2	Compressor discharge
C	Condenser heat-exchanger	3	Condenser outlet
D	Expansion valve	4	Evaporator inlet

KEY – LTHW CIRCUIT

COMPONENTS		SYSTEM OPERATING POINTS	
E	LTHW circulating pump	5	Heat emitter inlet (flow)
F	Heat-pump heater	6	Heat emitter outlet (return)
G	Gas-fired boiler	7	Heat pump inlet
H	Radiator heat emitters	8	Heat pump outlet

The thermal characteristics of the components shown in the heating system are estimated in the model, as described in the table below.

Heat emitters

The heat transmitted from the heating system into the dwelling is modelled as a function of the mean LTHW temperature, the room temperature (assumed 20°C) and the emitter heat transfer capacity. It is assumed that all the heat emitters act as radiators, with common heat transfer characteristics.

Radiator manufacturers specify their product's heat output capacity at a standard condition, typically 80/60°C LTHW flow/return and 20°C room air temperature. Then a correction factor is given for other LTHW or room temperatures, such that:

Radiator heat output, Q is given by:

$$Q_H = \left(\frac{MTD}{\widetilde{MTD}}\right)^n \widetilde{Q_H}$$

And mean temperature difference, MTD:

$$MTD = \frac{(T_{W5} + T_{W6})}{2} - T_{IA}$$

Where:

Q_H = radiator heat output (kW)

$\widetilde{Q_H}$ = radiator heat output at rated conditions (kW)

MTD = Mean temperature difference (K)

$\widetilde{MTD}$ = Mean temperature difference at rated conditions (K)

n = correction factor

T_{W5} = LTHW flow temperature (C)

T_{W6} = LTHW return temperature (C)

T_{IA} = Inside air temperature (C)

From inspection of manufacturers' technical specifications[42], a typical value for the correction factor n is 1.3.

We assume that the LTHW flowrate is set to meet the design heat load at the rated MTD, such that:

$$\dot{m} = \frac{\widetilde{Q_H}}{c(\widetilde{T_{W5}} - \widetilde{T_{W6}})}$$

Where:

$\dot{m}$ = LTHW mass flow-rate (kg/s)

c = LTHW specific heat capacity (kJ/kg/K)

[42] *Stalrad* technical brochure: www.stelrad.com/wp-content/uploads/2014/09/Stelrad-Vita-Series-LR.pdf

Using the above relationships, the LTHW flow and return temperatures corresponding to a given heat load Q_H can be determined as below:

$$T_{W5} = \left(\frac{Q}{\widetilde{Q_H}}\right)^{\frac{1}{n}} \widetilde{MTD} + \frac{Q}{2\dot{m}c} + T_{IA}$$

$$T_{W6} = \left(\frac{Q}{\widetilde{Q_H}}\right)^{\frac{1}{n}} \widetilde{MTD} - \frac{Q}{2\dot{m}c} + T_{IA}$$

LTHW System

It is assumed that the LTHW system operates at a constant flowrate, reflecting the current practice in most standard heating systems, such that:

LTHW heat flow, Q is given by:

$$Q_H = \dot{m}_W c(T_{W5} - T_{W6})$$

Where:

Q_H = heat flow (kW)

$\dot{m}_W$ = LTHW mass flow rate (kg/s)

c = LTHW specific heat capacity (kJ/kg/K)

T_{W5} = LTHW flow temperature (C)

T_{W6} = LTHW return temperature (C)

Heat Pump Condenser – Heat Exchanger

The heat pump transfers heat from the hot refrigerant gas into the LTHW via the condenser / heat exchanger. This is typically a counter-flow plate-type heat-exchanger. The rate of heat transfer is a function of the temperature difference between the hot refrigerant gas and the heating system water, and the heat transfer capacity of the condenser.

The total heat transfer in the condenser (which is assumed to be counter-flow) has been modelled using an iterative function to account for the superheated, saturated and sub-cooled phases within the heat-exchanger. The iterative function is based on the thermodynamic characteristics of the refrigerant gas and the following relationships:

Incremental heat flow, δQ is given by:

$$\delta Q_C = U\delta A(T_R - T_W)$$

Also, the total heat transfer from the refrigerant equals the heat gain by the LTHW:

$$Q_C = \dot{m}_R(h_2 - h_3) = \dot{m}_W c(T_{W8} - T_{W7})$$

Where:

δQ_C	=	Incremental heat flow (kW)
δA	=	Incremental heat exchanger area (m^2)
U	=	Heat transfer coefficient (kW/K/m^2)
T_R	=	Refrigerant temperature (C)
T_W	=	LTHW temperature (C)
Q_C	=	Total heat flow (kW)
$\dot{m}_R$	=	Refrigerant mass flowrate (kg/s)
h_2	=	Refrigerant enthalpy (kW/K/m^2) at condenser inlet
h_3	=	Refrigerant enthalpy (kW/K/m^2) at condenser outlet
$\dot{m}_W$	=	LTHW mass flow rate (kg/s)
c	=	LTHW specific heat capacity (kJ/kg/K)
T_{W7}	=	LTHW HP inlet temperature (C)
T_{W8}	=	LTHW HP outlet temperature (C)

We assume that the total condenser capacity (UA) has been sized to ensure that the refrigerant gas is fully condensed at the rated design conditions.

Heat Pump Compressor

The heat pump compressor draws the refrigerant gas from the evaporator outlet, and discharges it to the condenser inlet, at the higher discharge pressure.

The operation of the compressor has been modelled assuming:

- A fixed suction volume, depending on the size of the compressor
- A variable speed drive, which allows the volume flowrate to vary, to provide the required heat output
- A volumetric efficiency, accounting for inefficiencies due to physical limits set by valve arrangements, etc.
- An isentropic efficiency, to account for non-isentropic compression

The power absorbed by the compressor is modelled using the following relationships:

Power input, W:

$$W = \frac{\dot{m}_R (h_2 - h_1)}{\eta_V}$$

$$(h_2 - h_1) = \frac{(h_{2\bar{S}} - h_1)}{\eta_S}$$

Where:

W = Compressor power input (kW)

$\dot{m}_R$ = Refrigerant mass flowrate (kg/s)

h_1 = Refrigerant enthalpy (kW/K/m^2) at compressor inlet

h_2 = Refrigerant enthalpy (kW/K/m^2) at compressor outlet

$h_{2\bar{S}}$ = Refrigerant enthalpy (kW/K/m^2) at compressor outlet, assuming isentropic compression

η_V = Volumetric efficiency

η_S = Isentropic efficiency

The volumetric and isentropic efficiencies have been modelled using empirical relationships, as functions of the suction and discharge pressures, to approximate to published compressor characteristics[43]. The estimated values are illustrated in the charts below.

Figure 9-12 Estimated Isentropic Efficiency (R410A)

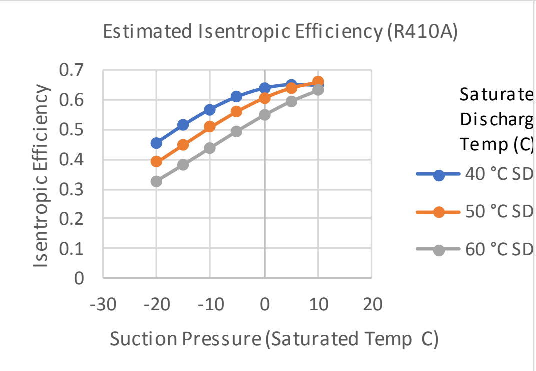
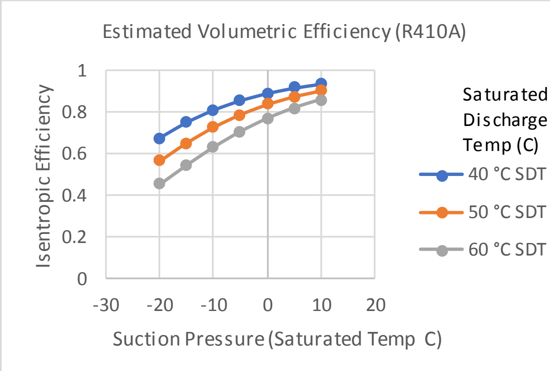


Figure 9-13 - Estimated Volumetric Efficiency (R410A)



Heat Pump Expansion Valve

[43] Source data: Copeland compressor selection software

The model assumes adiabatic expansion of the refrigerant gas, such that …

Refrigerant enthalpy:

$$h_4 = h_3$$

Where:

h_3 = Refrigerant enthalpy (kW/K/m^2) at expansion valve inlet

h_4 = Refrigerant enthalpy (kW/K/m^2) at expansion valve outlet

Heat Pump Evaporator Fan-Coil Unit

The rate of heat drawn from the outside air via the evaporator heat fan-coil unit is modelled as a function of the difference between the refrigerant saturated temperature and air on temperature, and the evaporator heat transfer capacity.

Heat transfer, Q_D :

$$Q_A = [UA]_A(T_{OA} - T_{R4})$$

And,

$$Q_A = \dot{m}_R(h_1 - h_4)$$

Where:

$[UA]_A$ = Evaporator heat transfer capacity (kW/K)

T_{OA} = Outside air temperature (C)

T_{R4} = Refrigerant temperature (C) at evaporator inlet

$\dot{m}_R$ = Refrigerant mass flowrate (kg/s)

h_1 = Refrigerant enthalpy (kW/K/m^2) at evaporator outlet

h_4 = Refrigerant enthalpy (kW/K/m^2) at evaporator inlet

Gas Boiler

The model assumes that the gas boiler operates at a constant gross efficiency of 81%. Although the actual efficiency will depend on the LTHW inlet and outlet temperatures (particularly for modern condensing boilers), this assumed to be a second-order effect on total energy consumption, and does not affect the electrical demand of a hybrid heat pump.

Boiler gas consumption, G :

$$G = \frac{Q_G}{\eta_G}$$

And boiler heat output, Q_F :

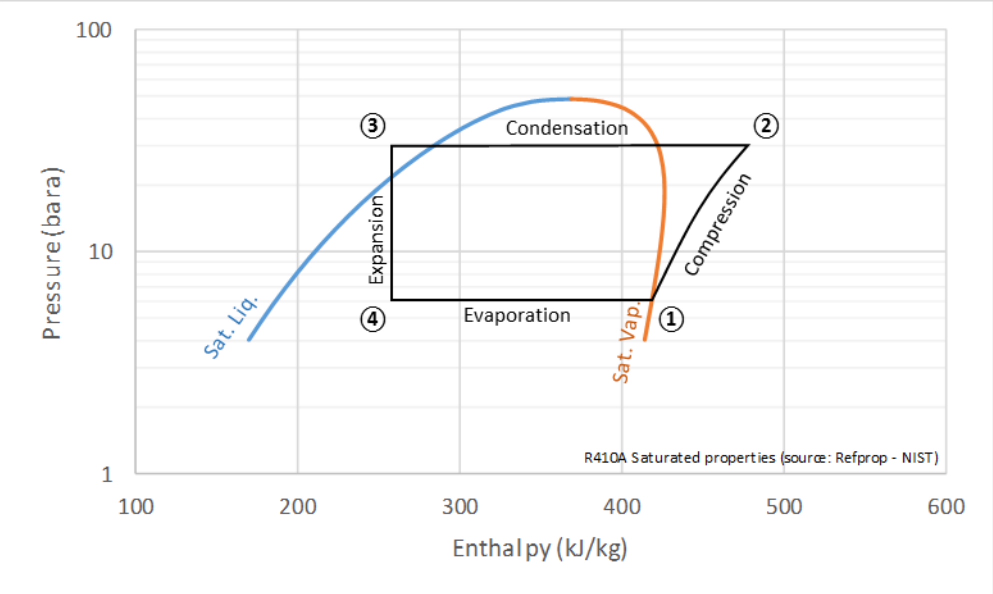
$$Q_G = \dot{m}_W c(T_{W5} - T_{W8})$$

Where:

G	=	Boiler gas consumption (kW)
Q_G	=	Boiler heat output (kW)
η_G	=	Boiler efficiency
$\dot{m}_W$	=	LTHW mass flowrate (kg/s) through the boiler
c	=	LTHW specific heat coeff. (kW/kg/K)
T_{W8}	=	LTHW temperature (kW/K/m^2) at boiler inlet
T_{W5}	=	LTHW temperature (kW/K/m^2) at boiler outlet

The model estimates the operating conditions of the refrigerant circuit by following a typical polytropic-compression / adiabatic-expansion cycle, which is illustrated in the pressure-enthalpy diagram below:

Figure 9-14 Heat pump refrigerant circuit - pressure vs enthalpy chart

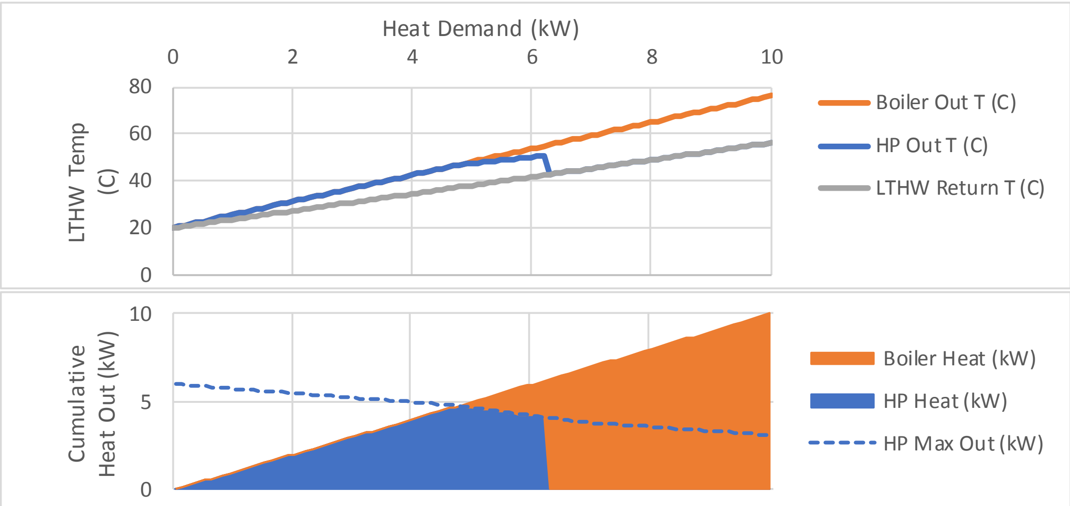


Hybrid Control Strategy

The model allocates the heat load between the heat pump and the gas-fired boiler according to two general modes:

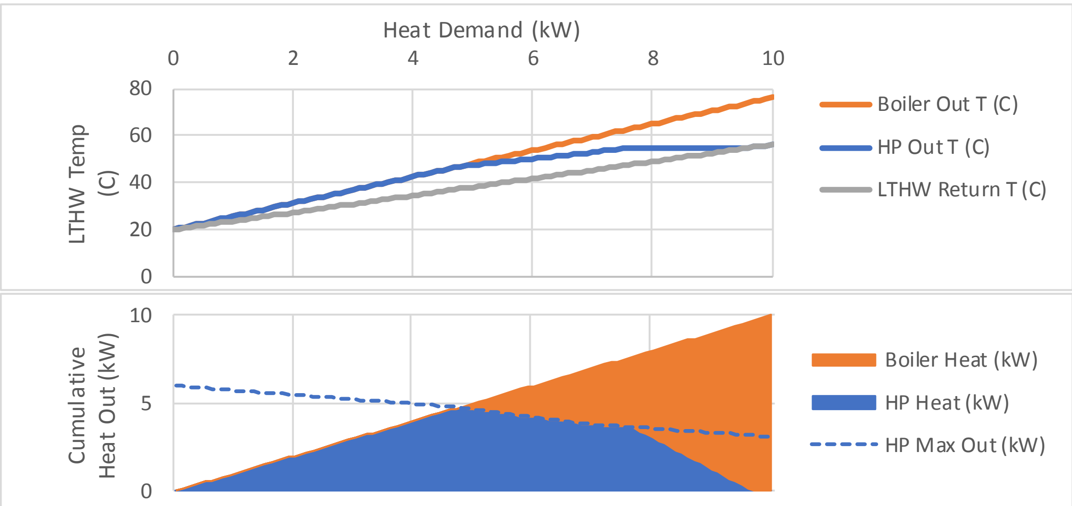
In “Switch Mode”, the heat pump operates while the LTHW flow and return temperatures are below the maximum limit (typically 55/50°C for low temperature heat pumps). The boiler provides top-up heating, and takes over entirely at high LTHW temperatures. This is illustrated below.

Figure 9-15 Hybrid heating in "Switch" mode



In “Parallel Mode”, the heat pump continues to operate in high heat load conditions – albeit providing less heat. This is illustrated in the charts below.

Figure 9-16 Hybrid heating in "Parallel" mode



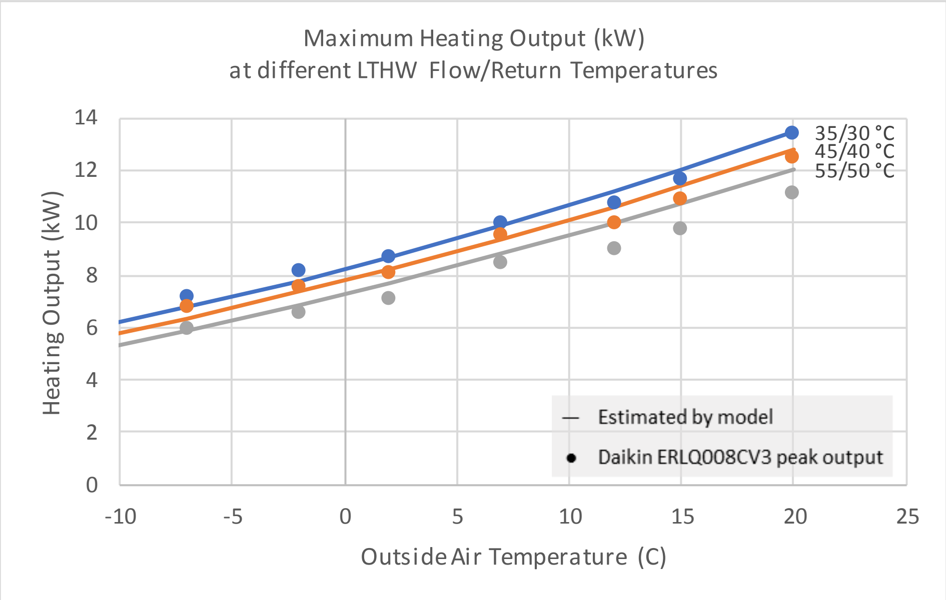
9.3.2 Calculations

The model uses iterative calculations to determine the operating temperatures of the LTHW and refrigerant circuits, while balancing the heat flows and meeting the boundary conditions set by the input parameters. This provides results for the heat output, power input and coefficient of performance (COP).

The model uses estimates for the capacities of the key components (e.g. compressor, evaporator and condenser). These have been set to align the results to specified heat pump performance as specified by manufacturers. Typically, the manufacturer’s specifications state the heat pump output capacity (kW) and power input (kW) at standard operating conditions, i.e. outside air temperature of +7 °C and LTHW flow/return temperatures of 35/30°C. Some specifications also show the heat pump characteristics at other operating conditions, (e.g. -7°C outside air temperature; 45/40°C flow/return).

In the chart below, the solid lines show the heat output estimated by the model, and the dots show a manufacturer's specified values of maximum heat output for a R410A heat pump of 8 kW nominal value (for the Daikin ERLQ008CV3 – see footnote[44]). These are "integrated values" for maximum heat output, taking account of frost and defrosting.

Figure 9-17 Maximum Heat Output (kW) - Estimates from model (lines) and rated values (dots) for 8 kW nominal capacity heat pump



The model gives a close estimate for LTHW flow/return temperatures of 35/30 and 45/40, but tends to over-estimate the heat output for higher LTHW temperatures (55/50). The table below provides the standard error of the model estimate compared to the rated values for peak heat output.

The chart below shows the corresponding comparison for estimated results and specified values for heating COP.

[44] Source: Daikin Technical Data Brochure EEDEN13-725 "Daikin Altherma low temperature split"

Figure 9-18 Heating COP (at maximum heat output) - Estimates from model (lines) and rated values (dots) for 8 kW nominal capacity heat pump

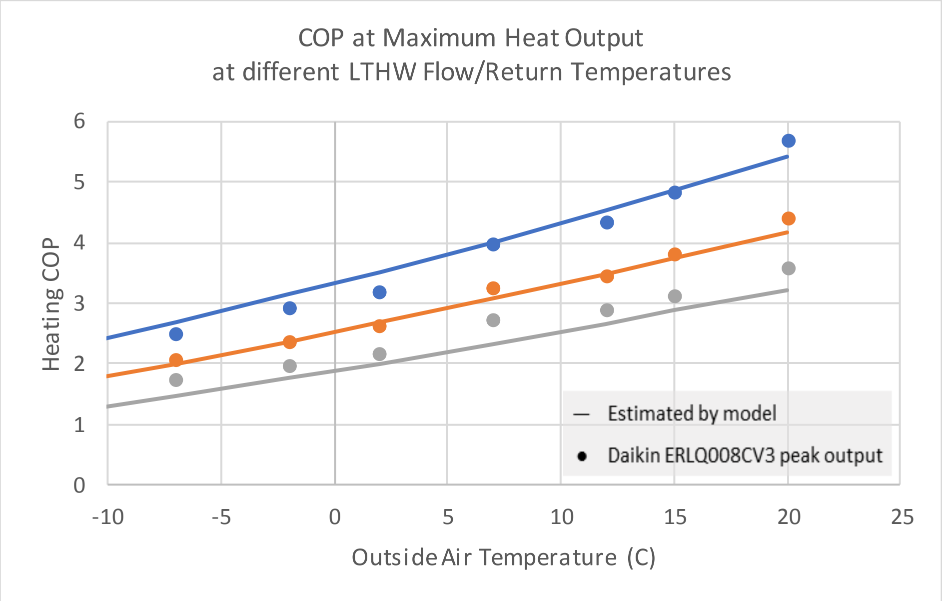


Figure 9-19 Standard Error of model compared to rated heat output (peak values), over range of -7 to +15 °C outside air temperature

LTHW flow/return temperature (C)	35/30	45/40	55/50	All
Standard Error in peak heat output	3.2%	4.6%	7.4%	4.7%
Standard Error in heating COP	5.6%	2.6%	10.9%	6.8%

9.4 Sources and assumptions on building archetypes

Table 9-1 Key characteristics of the six building archetypes studied

Building type	Thermal efficiency level	Floor area sources and assumptions	Heating demand sources and assumptions
Semi-detached	Typical	Floor area is the weighted average floor areas for the Semi-detached dwelling type in the English Housing Survey 2011-12.	Total gas demand is taken from the NEED dataset (2014 consumption data). The Typical semi-detached building is taken as the Median gas demand of Semi-detached buildings in the sample (13,000 kWh). Hot water is assumed to account for 15% of hot water and space heating demand based on *Energy Consumption in the UK*, November 2016 update, Table 3.07 (Domestic gas demand, values for 2012-2015). Annual space heating gas demand assumes total gas demand is comprised only of space heating and water heating gas demand (i.e. neglecting cooking and other uses).
Semi-detached	Insulated	Floor area is the weighted average floor areas for the Semi-detached dwelling type in the English Housing Survey 2011-12.	Total gas demand is taken from the NEED dataset (2014 consumption data). The Insulated Semi-detached building is derived by applying a 2,200 kWh reduction in the total gas demand in the Typical case, taken as the average saving for "solid wall insulation and loft insulation" in NEED Table 2 (2013). Hot water demand is assumed to be the same as for the Typical semi-detached case.
Semi-detached	Zero-carbon	Floor area is the weighted average floor areas for the Semi-detached dwelling type in the English Housing Survey 2011-12.	Annual space heating demand is assumed to be 46 kWh/m^2, based on Zero Carbon Hub, *Fabric Energy Efficiency for Zero Carbon Homes: A flexible performance standard for 2016*. Hot water demand is assumed to be the same as for the Typical semi-detached case.
Purpose-built flat	Typical	Floor area is the weighted average floor areas for all Flat dwelling types in the English Housing Survey 2011-12.	Total gas demand is taken from the NEED dataset (2014 consumption data). The Typical Purpose-built flat is taken as the median of all Purpose built flat buildings in the sample (6,500 kWh). Hot water is assumed to account for 15% of hot water and space heating demand based on *Energy Consumption in the UK* (2016), as described above.
Detached	Typical	Floor area is the weighted average	Total gas demand is taken from the NEED dataset (2014 consumption data). The

		floor areas for the Detached dwelling type in the English Housing Survey 2011-12.	Typical Detached building is taken as the median of all Detached buildings in the sample (17,100 kWh) rounded down to the nearest 1,000 kWh. Hot water is assumed to account for 15% of hot water and space heating demand based on *Energy Consumption in the UK* (2016), as described above.
Detached (large)	Typical	Floor area calculated by assuming annual kWh/m^2 equal to that for the Detached house, with floor area scaling up according to the total annual gas demand.	Total gas demand is taken from the NEED dataset (2014 consumption data). The Typical Detached (large) building is taken as the 90^{th} percentile of all Detached buildings in the sample (29,900 kWh) rounded down to the nearest 1,000 kWh. Hot water is assumed to account for 15% of hot water and space heating demand based on *Energy Consumption in the UK* (2016), as described above.

9.5 Data and assumptions used in lifetime cost comparison

Table 9-2 Product and installation cost data used in lifetime cost comparison. Low, central and high costs are shown for 2017 (and are used as starting points for the cost reduction scenarios of the same name).

Item	Unit	Low	Central	High
Product costs				
Gas boiler[45], 24 kWth	£/unit	800	800	800
Gas boiler, 36 kWth	£/unit	1,200	1,200	1,200
Heat pump, <5 kWth	£/kWth	1,234	1,285	1,468
Heat pump, 5-11 kWth	£/kWth	600	625	714
Heat pump, >11 kWth	£/kWth	333	500	583
HHP controller cost	£/unit	250	300	350
Hot water storage	£/litre	3	3	3
Installation costs				
HHP	£/building	2,000	2,500	3,000
Heat pump	£/building	2,000	2,500	3,000
Gas boiler	£/building	640	770	1,100
Replacement of emitters (if required)				
Semi-detached	£/building	1,800	1,800	1,800
Purpose-built flat	£/building	1,080	1,080	1,080
Detached	£/building	2,520	2,520	2,520
Detached (large)	£/building	3,240	3,240	3,240
Maintenance costs				
HHP	£/unit/yr	150	175	200
Heat pump	£/unit/yr	150	175	200
Gas boiler	£/unit/yr	150	175	200

[45] No range shown on gas boiler costs; cost is quoted for a mid-range boiler. The range is relatively small compared to the range in HP products and there is a higher level of certainty around future cost projections.

Table 9-3 Product and installation cost projections used in lifetime cost comparison

Item	Unit	Low	Central	High
Product cost projections				
HHP and standard HP	% reduction from current			
2030		0%	17%	30%
2040		0%	30%	30%
2050		0%	30%	30%
Gas boiler		None		
Installation cost projections				
HHP and standard HP	% reduction from current			
2030		10%	17%	30%
2040		10%	30%	30%
2050		10%	30%	30%
Gas boiler		None		

Table 9-4 Financial assumptions used in lifetime cost comparison

Item	Unit	Value
Discount rate		3.5%
Lifetime	yrs	15

Table 9-5 Fuel price assumptions[46]

Year	Domestic retail fuel price, £/kWh					
	Electricity			Gas		
	Low	Central	High	Low	Central	High
2017	15.73	15.95	16.28	3.80	3.98	4.23
2018	16.03	16.48	17.13	3.25	3.62	4.11
2019	15.97	16.64	17.62	3.24	3.61	4.19
2020	16.34	16.99	18.12	3.25	3.62	4.27
2021	16.89	17.42	18.69	3.22	3.59	4.32
2022	16.47	17.13	18.46	3.17	3.62	4.31
2023	16.96	17.44	18.82	3.23	3.71	4.40
2024	17.19	18.23	19.36	3.26	3.83	4.47
2025	18.45	19.46	20.31	3.33	3.94	4.55
2026	18.19	19.72	20.68	3.37	4.06	4.63
2027	18.04	18.99	19.61	3.45	4.18	4.71
2028	18.82	19.94	20.35	3.47	4.28	4.76
2029	18.35	19.43	19.84	3.54	4.39	4.88
2030	18.15	18.73	19.04	3.58	4.51	4.95
2031	18.15	18.73	19.04	3.58	4.51	4.95
2032	18.15	18.73	19.04	3.58	4.51	4.95
2033	18.15	18.73	19.04	3.58	4.51	4.95
2034	18.15	18.73	19.04	3.58	4.51	4.95
2035	18.15	18.73	19.04	3.58	4.51	4.95
2036	18.15	18.73	19.04	3.58	4.51	4.95
2037	18.15	18.73	19.04	3.58	4.51	4.95
2038	18.15	18.73	19.04	3.58	4.51	4.95
2039	18.15	18.73	19.04	3.58	4.51	4.95
2040	18.15	18.73	19.04	3.58	4.51	4.95
2041	18.15	18.73	19.04	3.58	4.51	4.95
2042	18.15	18.73	19.04	3.58	4.51	4.95
2043	18.15	18.73	19.04	3.58	4.51	4.95
2044	18.15	18.73	19.04	3.58	4.51	4.95
2045	18.15	18.73	19.04	3.58	4.51	4.95
2046	18.15	18.73	19.04	3.58	4.51	4.95
2047	18.15	18.73	19.04	3.58	4.51	4.95
2048	18.15	18.73	19.04	3.58	4.51	4.95
2049	18.15	18.73	19.04	3.58	4.51	4.95
2050	18.15	18.73	19.04	3.58	4.51	4.95

[46] Based on HMT Green Book Guidance Table 4-8: Retail fuel prices (March 2017)

Table 9-6 Carbon emissions factors

Year	Carbon emissions factor, $kgCO_2e/kWh$	
	Electricity[47]	Gas
2017	0.290	0.184
2018	0.258	0.184
2019	0.245	0.184
2020	0.217	0.184
2021	0.213	0.184
2022	0.177	0.184
2023	0.187	0.184
2024	0.202	0.184
2025	0.191	0.184
2026	0.168	0.184
2027	0.157	0.184
2028	0.130	0.184
2029	0.113	0.184
2030	0.117	0.184
2031	0.110	0.184
2032	0.091	0.184
2033	0.087	0.184
2034	0.076	0.184
2035	0.061	0.184
2036	0.065	0.184
2037	0.059	0.184
2038	0.054	0.184
2039	0.056	0.184
2040	0.052	0.184
2041	0.050	0.184
2042	0.047	0.184
2043	0.045	0.184
2044	0.042	0.184
2045	0.040	0.184
2046	0.038	0.184
2047	0.035	0.184
2048	0.033	0.184
2049	0.030	0.184
2050	0.028	0.184

[47] Based on HMT Green Book Guidance Table 1: Electricity emissions factors to 2100 (March 2017). Values taken for Grid-average, Consumption-based, Domestic sector.