Heat pump use in Scotland: an evidence review

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1 Executive summary

Heat pumps are an efficient way of producing heat from electricity; they operate by capturing the latent heat in the air, ground or water and using it for heating.

Heat pumps are expected to play a significant role in the decarbonisation of heat in Scotland; the Climate Change Committee has described them as a 'low-regrets' option[1] and they feature prominently in Scotland's Draft Heat in Buildings Strategy[2]. However, heat pump efficiency can vary across the heating season and in different buildings, meaning the costs and impacts on wider energy systems are dependent on context. This report presents the results of a desk-based evidence review to understand how heat pumps currently, or are likely to, perform in practice in Scottish buildings. The research identifies gaps in the available evidence which can inform future research. We also identify where there is best practice relevant to Scotland.

The evidence reviewed was a combination of grey literature, published research, academic papers, and case studies. For in-situ evidence of how heat pumps are likely to perform in Scotland, we reviewed both large-scale heat pump field trials and small-scale monitoring studies. The scope of the research was for both domestic and non-domestic buildings. However, the majority of relevant datasets identified relate to domestic settings.

1.1 Key findings

- Poor heat pump performance is most likely to arise due to poor design and specification; this means appropriate design and installation are the most important considerations to ensuring heat pumps perform well in Scotland.
- Heat pumps are a mature heating technology used in several European countries, including countries with colder winters than Scotland. The review found no evidence to suggest that heat pumps could not operate effectively in Scotland. In particular,

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[1] CCC (2020) Reducing emissions in Scotland – 2020 Progress Report to Parliament

[2] Scottish Government (2021) Heat in buildings strategy - achieving net zero emissions: consultation

there is no evidence that either the Scottish climate or building stock is generally unsuitable for the use of heat pumps.
- There are few large-scale, in-situ heat pump performance datasets specific to Scotland, its building stock and climate. However, the available evidence suggests that both domestic and non-domestic heat pumps in Scotland perform reasonably well in terms of efficiency. It also suggests there is occupant satisfaction with heat pumps.
- The performance of heat pumps is sensitive to a range of contextual factors. We found no evidence or indication that these factors present unusual challenges to the use of heat pumps in Scotland.
- Performance is based on technical but also non-technical variables. Heat pump systems are sensitive to design, installation, and user behaviours in ways that gas, oil and electric resistance heating are not. As the electricity demand of heat pumps is sensitive to complex interactions across these factors, it is difficult to draw very precise conclusions around comparative energy performance or comparative costs. The evidence demonstrates complex feedback loops between heat pump performance, levels of satisfaction and user behaviour.
- Based on these variables, there is evidence that heat pump performance could be maximised by building confidence in heat pump technology among consumers and the supply chain. Building better understanding, particularly in the use of monitoring data, more accurate heat loss calculations and advice for occupants, could improve the specification and use of heat pumps.
- Where running costs were monitored, heat pumps were cheaper to run than previous electric, oil or LPG heating systems and are a key outcome for occupant satisfaction. However, it is important to consider that this was based on the relative electricity and fossil fuel costs at the time of the studies.
- Based on the UK trials we reviewed, the most frequently identified cause of dissatisfaction among occupants relates to the control of heat pumps.
- Although more evidence is needed, the review suggests correct specification and sizing of heat pumps and heat emitters are critical determinants of heat pump performance. For optimum performance, design, specification and commissioning needs to be done on a bespoke basis per property.
- While hybrid heat pumps offer some advantages, the evidence on the balance between the contribution of the heat pump and boiler elements is highly varied, indicating emissions savings would be likewise variable.

1.2 Conclusions

The evidence review identifies some areas of confident knowledge for Scotland and also some gaps. We have drawn the following conclusions:

- There is a need for consumer and supply chain support to improve confidence and understanding of heat pump technology.
- It is crucial to ensure that users understand how to operate heat pumps to eliminate practices which reduce heat pump performance.
- There is a lack of available data on in-situ performance in Scotland. If in-situ performance monitoring could be collected systematically from more installations, this would significantly enhance our understanding of where performance might be improved.
- We found evidence gaps for variation across construction types, and the performance of some less common heat pump technologies, such as high temperature models.

- There was some evidence that rule-of-thumb methods and basic estimation are used to judge the correct size of heat pumps and emitters. The potential inaccuracies in sizing can lead to poor heat pump performance.
- We found there is value in installing monitoring equipment to enable fault identification. This would also provide in-situ data which may address some of the evidence gaps identified by this research. Ideally, this could include measurements at all four system boundaries of the heating system (see box on p12), allowing the isolation of individual components in terms of energy use; data at this level can also provide feedback for future design and specification.
- We identified potential benefit in providing support throughout the customer journey, from pre-sale and installation to after-sales stages, with a focus on improving understanding of the differences between heat pumps and combustion heating systems.We found evidence of a challenge in managing customer expectations. This was particularly around the expected electricity consumed by heat pumps in-situ (rather than presenting consumers with manufacturers' standardised ideal-condition performance metrics). Running-cost forecasts would be improved if based on in-situ conditions and if they highlighted the customer-specific factors which cause in-situ heat pump efficiency to vary from manufacturer calculations.
- Evidence suggests there is value in controls and displays which provide users with feedback on system operating efficiency; in particular, displays that show when any auxiliary boost heater in the system has switched on and which easily enable occupants to limit the use of boost heating functions.
- We found that the minimum available capacity for most heat pumps in the UK is 5kW, which is often more than needed for small, well-insulated properties. To reduce instances of lightly loaded systems, there is a need to improve understanding of customer demand in the supply chain.

Contents

2 Glossary of key terms

Term	Explanation
A/A Heat Pump	Air to air heat pump
Ancillary (equipment)	Equipment including, but not limited to, controls, circulating pumps and heaters installed along with a heat pump to create a complete installation.
ASHP	Air source heat pump (air to water only)
Auxiliary (heat)	Heat that is provided to supplement the heat pump (e.g., by an electric immersion heater or fan heater).
Bivalent	A hybrid heat pump system with two separate heat generators that may operate simultaneously – e.g., a heat pump and a boiler or a heat pump and a solar thermal collector.
Construction type	Refers to the materials a building is made of. In the UK construction types are generally referred to as traditional (solid or cavity walls made of bricks or blocks) and non-traditional (metal-framed, timber framed, pre-cast concrete, in-situ concrete).
CoP	Coefficient of performance of the heat pump for heating (instantaneous ratio of output thermal power to input electrical power).
DHW	Domestic hot water
DNO	Distribution Network Operator: Companies that own and operate the power lines and infrastructure connecting the transmission network to consumers.
Dynamic time of use tariffs	Electricity tariffs that provide different rates for each hour/half-hour of consumption and can change dynamically in response to conditions across the wider electricity system.
E7	Economy 7 tariff. This provides two rates of electricity, with the cheaper rate for 7 hours overnight. This tariff is usually used alongside storage heaters which charge overnight.
EASHP	Exhaust air source heat pump
Efficiency (relating to heat pumps)	The relative ratio of electrical energy in, and the heat energy out of the heat pump. The efficiency of heat pumps is measured using CoP (coefficient of performance).
GSHP	Ground source heat pump
Heat emitter	Transfers heat from a heating system into the space to be heated. Examples include radiators and underfloor heating.
HHP	Hybrid heat pump - combines an electrically driven heat pump with a boiler (usually gas powered).

Term	**Explanation**
MCS	Microgeneration Certification Scheme: A quality assurance scheme for microgeneration systems.
Monovalent	A term used to refer to a heating system that uses only one type of heat generator.
Oversized (relating to heat pumps)	Refers to instances where the heat pump is sized to give a higher heat output than is required to meet the peak heat demand of a building.
Peak heat demand	The peak rate of thermal energy in kW required to heat a building to set indoor temperatures, determined by the building fabric and ventilation heat loss at set and external temperatures dependant on location.
RHI	Renewable Heat Incentive
SCoP	Seasonal coefficient of performance. Where CoP is the instantaneous ratio of heat output to electricity input (which may vary across seasons), the SCoP is the ratio of total annual heat output to total annual electricity input. SCoP is a theoretical indication of the anticipated efficiency of a heat pump aggregated over a year, however in the reviewed evidence SCoP and SPF were used interchangeably to refer to both modelled and metered data.
SPF	Seasonal performance factor. The in-use ratio of heat out to electricity in over the year. In the reviewed evidence SCoP and SPF were used interchangeably.
System boundary	Defines which elements of the heat pump system are included when calculating the SPF or SCoP. Four system boundaries were defined as a result of the SEPEMO project. SPFH1 consists of the heat pump only, with expanding boundaries covering fan or pump power into the heat pump (SPFH2), back up heaters (SPFH3) and finally, system circulators or pumps and inbuilt auxiliary heaters (SPFH4).
U-value	A measure of the rate at which heat transfers through a structure. The better-insulated a structure is, the lower the U-value will be.
Undersized (relating to heat pumps)	Refers to instances where the heat pump output is too low to meet heat demand.
WSHP	Water source heat pump

3 Introduction

Scotland has ambitious climate change targets, with the heating of domestic and non-domestic buildings among the most challenging to decarbonise. The Climate Change Committee (CCC) recently reiterated the role of heat pumps (including hybrid systems) as a 'low-regrets' option[3], particularly in off-gas areas where electrification of heat is a focus. As set out in Scotland’s Draft Heat in Buildings Strategy, heat pumps have been identified as a strategic technology for Scotland: the rapid scale-up of heat decarbonisation will require widespread deployment of heat pumps.

Heat pumps are an established technology based on the refrigeration cycle developed in the nineteenth century and first used for space heating in the early twentieth century. Smaller domestic-scale models have been installed since the 1970s. Demand for heat pumps has increased with the current drive for the decarbonisation of heat. They are a proven technology and in some markets, such as Sweden, the technology is relatively mature.

An introduction to the different types of heat pumps examined here, and the general principles of their operation, can be found in Appendix 3.

This report draws on Scottish, UK and international experiences to produce an evidence base of the in-situ performance of heat pump technologies. The scope of the research was for both domestic and non-domestic buildings. However, the majority of relevant datasets identified relate to domestic settings. Based on monitoring data and field trials, we identify the key causes of variations in heat pump performance and suggest measures which can be taken to improve performance. We also explore the related issues of servicing and planning, and on-going innovations.

4 In-situ heat pump performance

This section explores the findings from current evidence of how heat pumps perform in-situ in Scottish buildings and in countries comparable to Scotland in terms of climate. Performance is considered in terms of running costs, efficiency, and user satisfaction. We examine performance in both technical and non-technical areas for single pump types and then explore the evidence for hybrid units.

4.1 Heat pump trials and monitoring data

To date, there have been two major field trials in the UK, including both air-source and ground-source heat pumps. The first was carried out by Energy Saving Trust (EST) and DECC (Department of Energy and Climate Change) in two phases spanning 2009 to 2012. The trial involved technical monitoring and analysis of user surveys. One of the main outcomes of the EST Phase 1 field trial was the revision of the Microgeneration Certification Scheme (MCS) heat pump installation standard in 2013. The standards seek to address issues surrounding the design and installation of domestic heat pump systems.

The second field trial was based on the Renewable Heat Premium Payment (RHPP) installations. The trial covered a total of 699 heat pump sites, with heat and electricity data collected between 2013 and 2015 at two-minute intervals. Online surveys were also conducted.

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[3] CCC (2020) Reducing emissions in Scotland – 2020 Progress Report to Parliament

DECC analysis of the data from the RHPP and EST trials indicates some improvement in SCoP over time. The improvements have been credited to the implementation of improved standards through the MCS[4,5].

BEIS is currently undertaking a trial of heat pumps in 750 properties across the UK[6] in three regional locations, which includes 250 properties in south-east Scotland. The project aims to demonstrate the feasibility of a large-scale roll-out of heat pumps and should address some evidence gaps identified in this report.

Monitoring data from small-scale studies was also included in the evidence review. This includes data from housing providers, other stakeholder organisations and results from academic papers which used in-situ data. Generally, the sample sizes for these studies were very small (as illustrated in Table *1*).

Table 1: Ranges of heat pump performance (CoP and SCoP) recorded across the reviewed trials and studies in the UK

Field Trial / Monitoring Study	**Year of Study**	**Heat Pump Type**	**Property Use**	**Sample Size**	**CoP Range** (short period)	**SCoP Range** (annual)	**System boundary**
Community Energy Scotland	2008-11	ASHP (non-dom)	Community building	4	0.5-3		Unknown
Community Energy Scotland	2008-11	GSHP (non-dom)	Community building	6	1.3-3.1		Unknown
Harrogate Council / De Montfort University	2009-10	GSHP	Domestic	10	1.9-2.9		Whole system (SPF$_{H4}$)
EST Phase 1	2009-10	GSHP	Domestic	49		1.5-3.4	Whole system (SPF$_{H4}$)
		ASHP		22		1.2-2.2	Whole system (SPF$_{H4}$)
EST Phase 2	2011-12	ASHP	Domestic	17		2.0-3.7	Whole system (SPF$_{H4}$)
						2.2-3.9	HP + fan (SPF$_{H2}$)
		GSHP		27		2.0-3.9	Whole system (SPF$_{H4}$)
						2.2-3.9	HP + fan (SPF$_{H2}$)
RHPP Trial	2013-15	ASHP	Domestic	293		1.54-4.43	Whole system (SPF$_{H4}$)

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[4] Energy Saving Trust (2013) The heat is on: heat pump field trials phase 2

[5] DECC (2014) Preliminary data from the RHPP heat pump metering programme

[6] The BEIS Electrification of Heat Demonstration Project

Field Trial / Monitoring Study	Year of Study	Heat Pump Type	Property Use	Sample Size	CoP Range (short period)	SCoP Range (annual)	System boundary
		GSHP		92		1.64-4.37	Whole system (SPF_{H4})
BEIS non-domestic RHI	2014-16	GSHP & WSHP	Non-domestic	19		2.24-4.49	Whole system (SPF_{H4})
						1.24-4.5	HP + fan (SPF_{H2})
RECC analysis of Ofgem data	2015-19	ASHP & GSHP	Domestic	300		1.24-4.5	Unknown
Daikin / Leeds Beckett University[7]	Pre-2016	Hybrid	Domestic	9		3.1-4.0	Unknown
University of Ulster	2018	High Temp	Domestic	1	1.82-2.38		Unknown
Hebridean Housing Partnership	2020	ASHP	Domestic	17	1.8-2.9		HP + fan (SPF_{H2})
Local Energy Scotland Case Study	2020	GSHP (non-dom)	Community hall	1	2.9		HP + fan (SPF_{H2})

4.2 Findings

4.2.1 Technical performance

Efficiency

The results in Table 1 show clearly that performance varies, even within datasets where variables such as property type, location, installation and servicing regimes are similar, such as the 17 Hebridean Housing Partnership properties.

Making comparisons between different case studies is complex and it is also currently difficult to judge performance improvements over time. Different locations, construction types and heat pump types present a challenge; in addition, different system boundaries (see Figure 1) are used across the datasets.

Results from studies which looked at the performance of the heat pump and fan only (SPF_{H2}) cannot be directly compared to those which measure efficiency across the whole system (SPF_{H4}) as it is not possible to separate the impact of the auxiliary direct electrical elements such as immersion heaters in hot water cylinders. Additionally, it is hard to draw conclusions from studies where the system boundary is not clearly explained.

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[7] Referenced in BEIS (2016) Evidence Gathering - Low Carbon Heating Technologies

We found evidence of performance from individual manufacturers (see Table 2 for an example).

System boundaries

System boundaries describe which parts of a heat pump system are being measured to calculate system efficiency (CoP). Four system boundaries were defined as a result of the SEPEMO project, which are illustrated below (Figure 1).

- SPF_{H1} consists of the heat pump only.
- SPF_{H2} includes the source fan/pump, compressor and control electrical energy inputs so is directly comparable to alternative fossil fuel heat sources such as condensing gas boilers.
- SPF_{H3} includes back up heaters.
- SPF_{H4} includes system circulators or pumps and inbuilt auxiliary heaters.

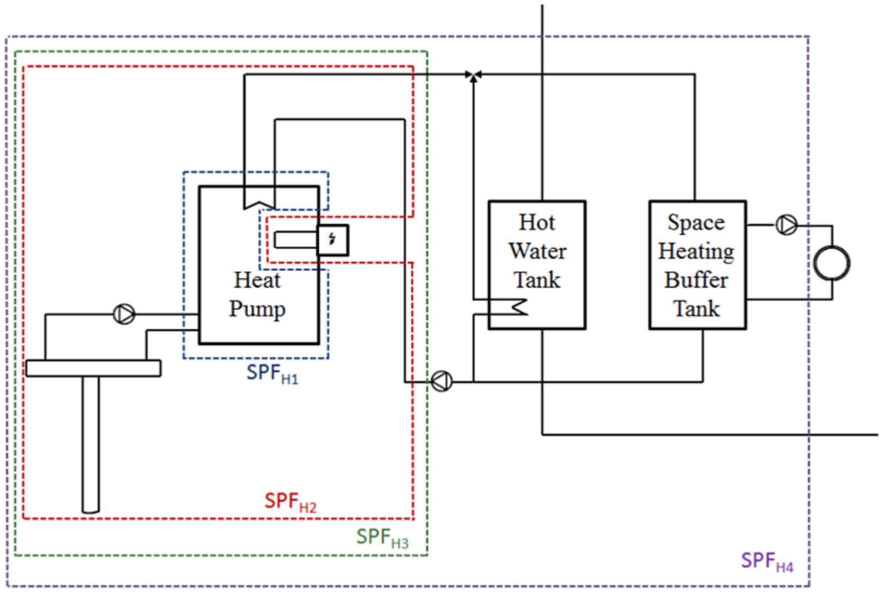
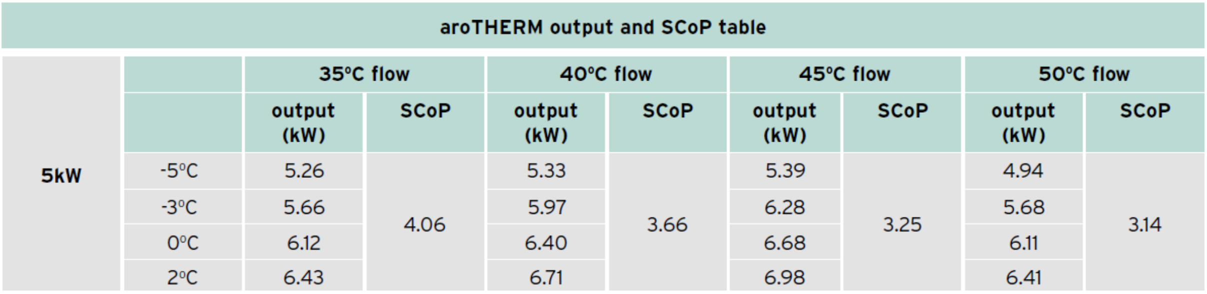


Figure 1: Explanation of heat pump system boundaries
Image from Carroll, P. et al. (2020) published under Creative Commons 4.0

Compared to the reviewed in-situ performance data, the manufacturer estimates for SCoP are higher as they are likely based on laboratory test conditions and do not account for external factors identified in this research.



aroTHERM output and SCoP table

		35°C flow		40°C flow		45°C flow		50°C flow	
		output (kW)	SCoP	output (kW)	SCoP	output (kW)	SCoP	output (kW)	SCoP
5kW	-5°C	5.26	4.06	5.33	3.66	5.39	3.25	4.94	3.14
	-3°C	5.66		5.97		6.28		5.68	
	0°C	6.12		6.40		6.68		6.11	
	2°C	6.43		6.71		6.98		6.41	

Table 2: This is an example of a manufacturers' table of heat pump performance for the Vaillant aroTherm 5kW model[8]. It shows the expected SCoP relative to external temperature and flow temperature.

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[8] Vaillant aroTHERM specifications

Running costs

The running costs of heat pump systems are difficult to estimate, being impacted by a number of variables (see Table *1*) including CoP, property use and heat pump type. Additional variables include the electricity tariff and user behaviour, as well as the specification and commissioning of the heating system that would determine the SCoP. Maintenance is also recognised as an issue and this is covered later in section 7.1.

Some small-scale monitoring projects we reviewed[9] used running costs as their key metric. Whilst running costs are an important outcome for occupants, many studies did not report cost data. This could be due to the large number of variables which impact on them and perhaps because these figures may become out of date as electricity prices change. Additionally, some monitoring studies measured the cost of all electricity usage, again limiting the usefulness of this data.

Across the studies where running costs were monitored, heat pumps were cheaper to run than previous electric, oil or LPG heating systems, but it is important to consider that this was based on the relative electricity and fossil fuel costs at the time of the studies. Despite this experience, issues including unknown future costs due to the volatility of fuel prices, or the high costs associated with technical faults were reported as concerns by occupants. The challenge can be illustrated through a comparison with fossil fuel costs (Table 3, based on 2021 prices), where the running costs of an oil heating system are currently lower than natural gas.

Table 3: Annual fuel costs for heating types, based on January 2021 Sutherland tables[10], 3-bedroom house. Note the current low price of oil reflected in the running costs

Heating technology	Annual running costs
Storage heaters	£2166
Natural gas boiler (condensing)	£857
LPG boiler (condensing)	£1682
Oil boiler (condensing)	£803
Air source heat pump (assumed SCoP 2.5)	£1374
Ground source heat pump (assumed SCoP 3.0)	£1171

Monitoring of 15 properties with ASHPs found that the annual heating cost per m^2 varied from £6 to over £16 per year and found that the most expensive properties to run were the oldest due to poor fabric efficiency[11]. The case studies from the RHPP trial also demonstrated a large range in cost per m^2 from £4 to over £16. This data demonstrated that the bigger the area of the house in the sample, the lower the cost per m^2 tended to be, which would be expected as the ratio of wall area to floor area would be lower. The

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[9] All of the National Energy Action monitoring studies, and the monitoring data shared by De Montfort University (2017)

[10] www.sutherlandtables.co.uk

[11] De Montfort University (2017). Costs were calculated based on KWh per annum per m^2 and were intended to demonstrate the variation in cost rather than provide accurate calculations of costs.

RHPP trial measured cost on the basis of total bills rather than heat pump operating costs specifically.

Other studies used ‘satisfaction with running costs’ as a metric. For example, in the first EST trial 75% of participants were satisfied with running costs. This approach is subjective and is influenced by other aspects of the occupant experience, particularly the previous heating system and expectations of running costs.

Savings (or changes in running costs) are dependent on the previous heating system used, the tariff (cost of electricity used), and the heat requirement of the building. The RHPP field trial found that the highest fuel cost savings were for heat pump systems displacing electric heating on standard tariffs, followed by electric E7 tariffs. Additionally, in all cases savings were higher for GSHP than ASHP systems. These findings are expected given that heat pumps are much more efficient than direct electric heating, and GSHPs should be more efficient than ASHPs, as well as more likely to be installed in a larger building with higher heat requirement.

As part of their analysis of the RHPP data, the UCL Energy Institute modelled SCoP results to predict the pattern of savings in fuel costs across different fuel types[12]. This was based on the percentages of heat pump installations where the SCoP was high enough to result in bill savings[13]. It is worth noting that the RHPP scheme was not intended to fund the replacement of gas-fired heating with heat pumps. Therefore, none of the properties in the trial were previously using natural gas, but it was included in the model as the current best performer among non-renewable fuels.

This model predicted that for ASHPs, all households using a standard electricity tariff and 89% of households on an Economy 7 tariff would be expected to make bill savings. 78% using coal, and 95% using LPG would be expected to make bill savings, compared to only 2% using oil and 13% using natural gas based on the fuel prices at the time of the study. Anticipated savings were more widespread for GSHPs for all fuel types.

4.2.2 Non-technical performance analysis: user satisfaction

Evidence shows that user satisfaction with heat pumps is a product of various factors[14] including (but not limited to):

- customer journey
- controllability
- perceived comfort
- advice and information provided by the installer
- experience with previous heating system
- bills
- the installation process
- perceived environmental benefits
- time taken to fix faults
- noise levels.

The sources we reviewed did not provide evidence relating to all of these factors. This may be due to the research design (participants were not asked directly about certain issues), or to these issues not being pertinent to research participants. We found

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[12] Based on EST Fuel prices and carbon factors from 2016

[13] SCoP 2.44 for ASHP and 2.71 for GSHP (both measured at the SPF_{H4} system boundary)

[14] UCL Energy Institute (2017) Case Studies Report from the RHPP Heat Pump Monitoring Campaign

evidence around controllability, perceived comfort, noise, comparisons to previous heating systems and advice and information from suppliers and installers. The evidence demonstrates complex feedback loops between heat pump performance, levels of satisfaction and user behaviour.

Experience with previous heating system

Across the reviewed evidence, satisfaction with heat pumps is generally high despite the issues discussed below (experienced by a sizeable minority in most studies) and in some cases despite significant disruptions and breakdowns[15]. Satisfaction is relative to the user's experience of their previous heating system. When compared with electric storage heaters or solid fuel systems generally, users report both improved comfort and reliability. There is little evidence on user satisfaction when replacing natural gas heating with heat pumps. However, the ongoing BEIS Electrification of Heat project[16] will provide data from properties on the gas grid.

Controllability

The evidence indicates that a high proportion of users are satisfied with domestic hot water provision from heat pumps and with space heating[17]. For example, of the 38 participants in Phase 2 of the EST trial, 84% were satisfied with hot water provision and 80% with space heating. Of 120 properties in Orkney 73% of respondents were satisfied with domestic hot water provision and 59% with space heating[18]. However, within this same sample in Orkney, 1 in 3 participants reported that their overall heat pump satisfaction was worse than with their previous storage heaters. In this case it is assumed that dissatisfaction is related to controllability, as more than half of respondents reported finding it difficult to use the heat pump's controls and displays. The evidence demonstrates that controllability is a common source of user dissatisfaction.

Across the 18 evidence sources which referred to user satisfaction, 13 sources described user control as a source of dissatisfaction, making it the most frequently identified cause of dissatisfaction in this study. In the EST field trial (Phase 1) the main complaints among participants were over two-fifths of users not knowing how to operate their system for optimum efficiency and economy, and nearly a third having difficulties understanding operating instructions[19]. The control panel itself seems to be very important in perceptions of user-friendliness. Field trials and surveys also revealed that dissatisfaction is caused by hard-to-understand operating instructions.

Surveys with 83 social housing tenants in Shetland found that 80% of tenants using Mitsubishi Ecodan ASHP found their system easy to use, compared to 36% using NIBE F470 or F410 exhaust air heat pumps and 32% using Stiebel Eltron GSHP. The study suggested that ease of control was associated with heat pump models with an electronic interface to assist with trouble shooting.

Perceived comfort

There is evidence that heat pumps provide good thermal comfort, for example 83% of participants in the EST trial reported heat pumps made their home warm and comfortable. A small monitoring study of 8 properties where solid fuel or storage heating systems were replaced with ASHP found that homes were warm and comfortable for 7

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[15] UCL Energy Institute (2017) Case Studies Report

[16] The BEIS Electrification of Heat Demonstration Project aims to demonstrate the feasibility of a large-scale roll-out of heat pumps through installations in 750 homes.

[17] Energy Saving Trust & DECC (2013)

[18] James Hutton Institute & Orkney Housing Association Ltd (2014)

[19] Caird, S. Et al. (2012)

of 8 participants (compared to 3 of 8 with the previous systems)[20]. However, some studies also identified issues with thermal comfort such as temperature differences across the home, in particular low temperatures upstairs[21], slow warm up times (reported by over 20% of participants in Phase 1 of the EST trials) and dissatisfaction with high night-time temperatures[22]. The latter could be due to actual discomfort at night or driven by a belief that night-time operation of heating is wasteful.

Noise levels

Noise from ASHP fans was also identified as a cause of dissatisfaction, although this did not seem to be as prominent as user control issues. In the EST field trial (Phase 1) 19% of participants reported that intrusive noise was a problem, and this was a problem for proportionally more (33%) social residents than private householders (9%) and for more ASHPs (26%) than GSHPs (15%)[23]. A poorly installed heat pump will emit more sound than expected, and therefore installer knowledge plays a key role. A recent white paper[24] from the European Heat Pump Association (EHPA) concludes that sound issues are exacerbated by false expectations resulting from the knowledge gap between industry and the public and policymakers. The sound perception of heat pumps is also closely linked to the installation of the unit. The location, surrounding environment, and visibility play a key role in user perceptions of noise.

Technical support

The evidence suggests that dissatisfaction with heat pump performance is also associated with a lack of technical support and advice from suppliers and installers, as well as difficulties in getting advice, or knowing who to contact. Advice is often sought on heating controls and issues with inbuilt auxiliary heaters which are set up by the installer initially. Re-setting heat pump controllers after users had altered them was identified as a major reason for callouts by several manufacturers[25]. This illustrates the complex relationship between performance, satisfaction, user control, user behaviours, and advice from the installer.

In conclusion, the evidence suggests that heat pump users tend to be satisfied with their heating systems. Where consumers are dissatisfied, ease of use and controllability appear to be key causes of this, across a majority of the studies we reviewed. The reviewed evidence provided a number of other reasons for consumer dissatisfaction including, noise, lack of technical support and lack of advice from suppliers. This however was often anecdotal evidence, for example given as an additional comment in a survey rather than as a response to a direct question about the issue. This means it is difficult to get a sense of the scale of these issues among heat pump users.

4.2.3 Non-technical performance analysis: customer journey

User satisfaction is closely related to the customer journey - that is, the steps from pre-installation through to operation. A poor experience at any stage of the customer journey could impact consumer perceptions of, and satisfaction with, heat pump performance. Recent research on the consumer journey when installing low carbon heating suggests that over-promising of heat pump efficiency and/or cost savings at the pre-installation stage, is a cause of customer dissatisfaction with heat pump performance[26]. The

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[20] National Energy Action (2018) Project CP752

[21] Hjaltland Housing Association

[22] Boait, P.J. et al (2011)

[23] Caird, S. et al. (2012)

[24] EHPA (2020) Heat Pumps and Sound

[25] BEIS (2016) Evidence Gathering – Low Carbon Heating Technologies: Domestic High Temperature, Hybrid and Gas Driven Heat Pumps: Summary Report

[26] CAS (2020) Fit for the Future - Putting consumers first in the move to net zero

reviewed evidence provided some examples of exaggerated performance figures and unrealistically low running costs provided to customers at the pre-installation stage. For example, interviews with seven social housing tenants using GSHPs revealed that five tenants were originally quoted extremely low running costs which were then greatly exceeded[27]. These tenants reported a poor overall experience with their heat pumps. Another study of 10 GSHP installations noted that some participants felt that expected cost savings were not realised[28].

Analysis conducted by RECC[29] of Ofgem data on 300 domestic installations, compared installer efficiency predictions with actual efficiency and found almost no correlation between the two, with the actual being lower in nearly all cases. Further analysis of the full dataset of over 2,000 installations is currently being conducted. RECC has suggested that the MCS methodology (which uses SCoP at system boundary SPF_{H2}) tends to overestimate in-situ efficiency forecasts and underestimate the likely electricity costs for consumers[30]. This is because SPF_{H2} does not account for factors such as backup heating or hot water operation. An evaluation of the SCoP methodology is beyond the scope of this report, however RECC and BRE have suggested that it be reviewed. The recently published MCS Heat Pump Guide[31] outlines best practice for undertaking performance estimates using the methodology and the need for installer caution. The guide acknowledges the limitations of SCoP and states that it is *"inevitable that the actual efficiency achieved will be less than the SCoP prediction."* The evidence we have reviewed suggests that accurate cost forecasts are an important factor in managing customer expectations for a successful customer journey. When installers are providing running cost forecasts it is essential that they understand the limitations of SCoP and the extent to which this will affect estimates. This could be addressed by installer training.

Additionally, where consumers experience teething problems with a new heat pump, there is evidence from one study that the speed and success of resolving these is key in shaping perceptions of their heating systems[32].

4.3 Hybrid heat pumps (HHP)

It is worth considering the evidence for hybrid heat pumps - that is a system that combines any type of heat pump with any form of combustion heating (see Appendix 3 - Heat Pump Operationfor more detail).

The reviewed evidence (for example Element Energy's 2017 report on hybrid heat pumps, and Western Power Distribution and Wales & West Utilities' 2019 FREEDOM project) showed that the share of heat demand met by the heat pump element varied from 1% to 96% depending on the specification and consumer behaviours. It depends on capacity, set up, overall heat demand, property type, heat emitters, heating schedule and user behaviour. The capacity of the heat pump is fundamental in determining what proportion of the heat demand it can meet and therefore the emissions savings of a HHP. The CoP will also determine the proportion of heat demand, as when it drops below a set threshold it could be more economical and less carbon intensive to heat with the combustion element of the HHP.

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[27] Consumer Focus Scotland (2012) 21st century heating in rural homes

[28] Boait, P.J. et al. (2011) Performance and control of domestic ground-source heat pumps in retrofit installations

[29] RECC (2020) Analysis of Ofgem 'Metering for Payment' Data

[30] RECC (2018) Background to Heat Pump Seasonal Coefficient of Performance (SCOP) metric and an analysis of its use

[31] MCS & RECC (2020) Domestic Heat Pumps: A Best Practice Guide

[32] Consumer Focus Scotland (2012) 21st century heating in rural homes

Heating schedules can also drastically alter the proportion of demand met by the heat pump. The high peaks of a twice-a-day schedule require high flow temperatures and must therefore be met by the boiler instead of the heat pump. Analysis by Element Energy[33] found that the annual emissions savings achieved by a HHP would be 55% under a continuous heating schedule, but only 18% for a twice a day heating schedule. A HHP used in the same way as a combustion system will mean that the combustion system operates more frequently, and therefore the carbon reduction impact will not be as great as if it were operated continuously.

The main determinant of the balance between heat sources seems to be the diversity of heat demand, with properties that are well-insulated and retain heat being heated primarily by the heat pump element[34]. Properties and the heat demand of occupants should be assessed on a case-by-case basis when specifying and commissioning a HHP system, though we found the evidence base to support decisions on the suitability of a HHP system for different building types to be very limited.

One advantage of a HHP is that it can be retrofitted to buildings with existing heat emitters designed for combustion systems operating at high temperatures. We would expect systems with low temperature heat emitters to typically meet a higher proportion of heat demand through the heat pump compared to high temperature emitters, though in-situ studies have not reported data on this effect.

The performance of HHPs, in terms of both fuel cost and comfort depends on consumer behaviour, and the ability of ‘smart’ controls to influence this behaviour. The FREEDOM project[35] tested a control strategy optimised for fuel costs. The project was run by two network companies. It aimed to run hybrid heating systems at least cost to the householder. Due to low natural gas prices, heat pumps provided between 1% and 20% of the heat for properties on the gas network. For LPG systems however around 80% of heating load was switched to the ASHP. Consumers with LPG boiler hybrid systems made significant savings on their heating bills.

The FREEDOM project found that at today’s prices, it is rarely cost-effective to operate the heat pump element on natural gas; and that were electricity prices to remain stable and natural gas prices to increase by 50%, it would only be worthwhile for the heat pump to take 40% to 50% of the heat load.

Overall occupant satisfaction and comfort levels were high. A few households had a strong preference for 'burst heating' which is incompatible with decarbonisation using heat pumps. Temperature control was a concern for participants, and highlights the need for ongoing education and support, particularly on the heat pump operation. Occupants also experienced cost savings and improved comfort in a small project to replace electric storage heaters with natural gas / ASHP hybrid system[36]. This was despite none of the residents being able to set their own heating times within the HHP system.

4.4 Evidence gaps

4.4.1 Quantity and quality of monitoring data

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[33] Element Energy (2017) Hybrid Heat Pumps

[34] Ibid.

[35] Western Power Distribution and Wales & West Utilities FREEDOM Project

[36] National Energy Action (2017) Daikin Altherma hybrid heat pumps, Copeland and South Tyneside (CP747)

The evidence review was focussed on the UK and also included evidence from European countries with similar climates to Scotland[37]. The review revealed only a small number of high-quality monitoring datasets of heat pumps in-situ.

Firstly, there are only two studies that contained sample sizes of over 50 properties to draw conclusions from (RHPP: 385 and EST Phase 1: 83), and most of the remaining studies were fewer than 20 properties. It is important to recognise the evidence available for review dates back some years. On-going studies will provide more detailed and up to date results that will significantly enhance our understanding. For example, the BEIS Electrification of Heat trial will provide monitoring data for 750 heat pumps, including air source, ground source, hybrid and high temperature heat pumps.

During the evidence search we found 149 sources of which many of the monitoring studies were using estimated heat output figures rather than actual metered heat output. We also found that in some instances where heat meters were fitted to heat pump systems, no regular monitoring was being conducted.

The analysis of the RHPP monitoring data is one of the largest and most comprehensive evidence sources of in-situ heat pump performance in the UK. However, the analysis found various limitations to the data including systematic errors[38] such as heat meters being misread and incorrect placement of heat meters. The latter was also an issue during the EST Phase 1 trial[39]. Six sites were removed from the EST trials for this reason, and instruments were replaced on a further five sites.

4.4.2 Comparing data

Comparisons between field trials can be complex given the use of different system boundaries when measuring system performance. It is also complex to make comparisons where studies use running costs as a metric as these are dependent on context, electricity tariffs and, where only cost savings are presented, the previous heating type.

4.4.3 Cold weather

We found limited evidence of the impact of cold weather on heat pump performance. A large number of sources made no reference to variations based on seasonal or weather patterns. The RHPP field trial only reported SCoP figures (across the season), so the efficiency of heat pump performance during specific periods of cold weather could not be isolated. However, the final report states that average winter space heating flow temperatures were generally low (<45°C), with only a few sites showing average winter flow temperatures >50°C. Low flow temperatures would be expected to result in good efficiencies. Among the five studies where weather or outdoor temperatures were investigated, there was some evidence that lower external temperatures are associated with increased running costs and reduced comfort[40,41,42]. Due to the small sample sizes of these monitoring studies, we would suggest that further research is required to determine the impact of cold weather on heat pump performance.

The FREEDOM project reported that the ASHP element of hybrid heat pumps achieved “good coefficients of performance”[43] even when operating at temperatures below -6ºC. However, no actual CoP figures were published.

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[37] Defined as temperate maritime conditions

[38] UCL Energy Institute (2017) RHPP Heat Pump Study: Note on Systematic Errors in Physical Monitoring Data

[39] DECC (2015) Heat Meter Accuracy Testing

[40] Boait, P.J. et al. (2011) Performance and control of domestic ground-source heat pumps in retrofit installations

[41] National Energy Action (2017) Daikin Altherma hybrid heat pumps, Copeland and South Tyneside (CP747)

[42] National Energy Action (2017) Heat pumps for park homes, Basingstoke YES Energy Solutions (CP753)

[43] Western Power Distribution (2018) FREEDOM Project Final Report

4.4.4 Construction type

We found very little evidence of the impact of construction type on heat pump performance. This variable was not analysed in any of the large-scale trials we reviewed. For example, the RHPP trial collected information such as dwelling age for privately owned dwellings but not socially rented ones. No analysis was conducted using the property data. Smaller datasets from monitoring studies indicate that there is a wide variation of performance within the same property construction types[44].

4.4.5 Cost savings

There is very little data of the cost savings which can be expected for heat pump installations when they are replacing natural gas heating systems. The two largest UK trials (EST and RHPP) provide no data for properties which previously used natural gas for heating. However, the ongoing BEIS Electrification of Heat project[45] will provide data from properties on the gas grid.

5 Variations in heat pump performance

This section draws on evidence from across the UK and European studies and examines factors that cause variations in heat pump performance.

5.1 Identified causes

Gleeson et al.'s analysis of several European field trials[46] found that the main features which broadly correlate with efficient heat pump operation are:

- Use of low temperature heat emitters.
- Minimal use of resistance heating.
- A higher proportion of space heating demand compared to hot water demand.

Through our review of field trials and monitoring data we have also found that other factors can impact on the efficiency of heat pump operation. These immediate causes are often the result of both technical and behavioural factors which cannot be easily disentangled. These are considered below in more detail. Figure 2 summarises the immediate causes of variation and illustrates the complex web of both behavioural and technical factors which result in these.

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[44] Hebridean Housing Partnership (2020) Monitoring data from 17 ASHPs

[45] The BEIS Electrification of Heat Demonstration Project aims to demonstrate the feasibility of a large-scale roll-out of heat pumps through installations in 750 homes.

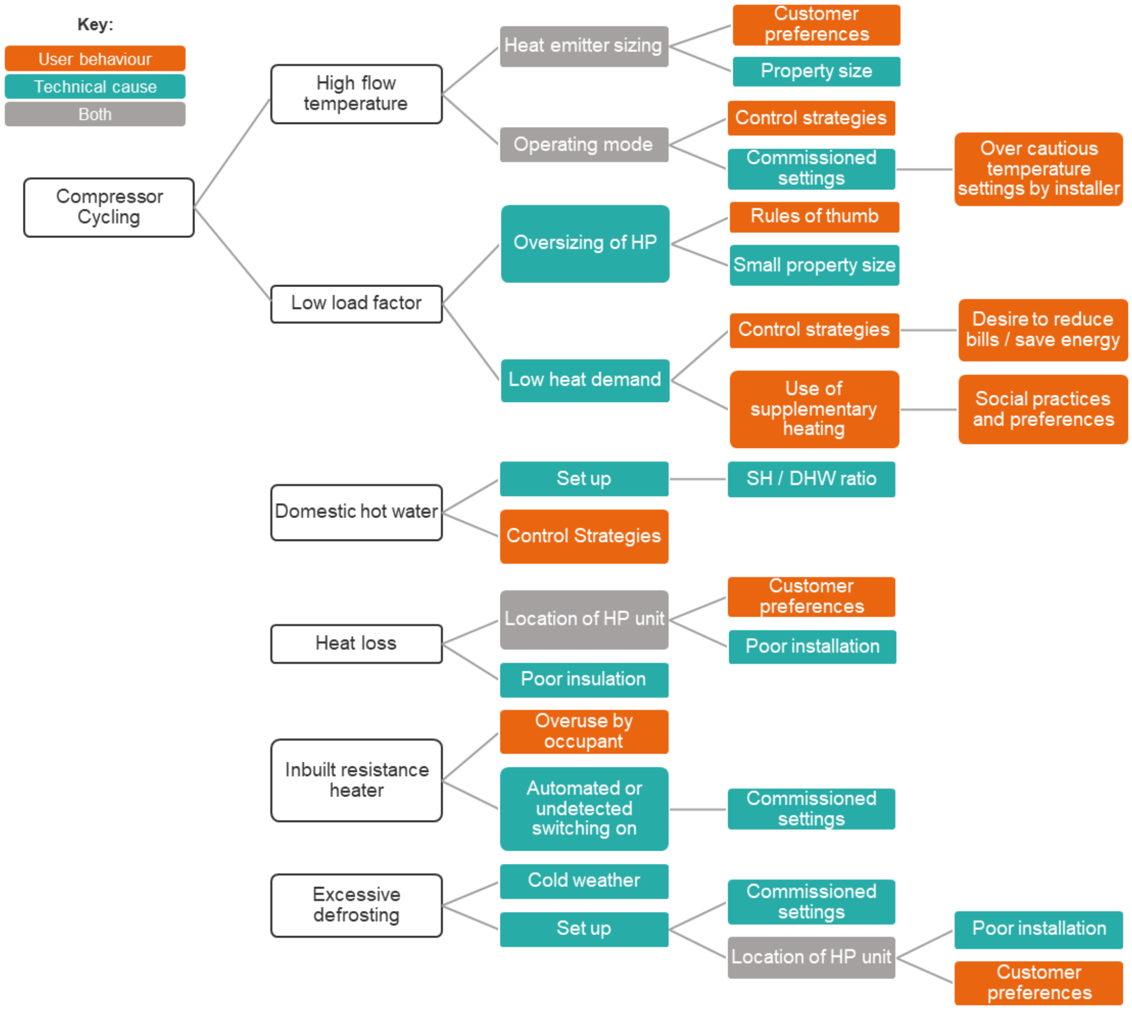

Figure 2: Diagram of immediate and underlying causes for the variations in heat pump performance. This diagram summarises the factors identified across all reviewed sources, and we found no evidence to indicate any special circumstances for heat pump performance in Scotland.

5.1.1 Compressor cycling

Excessive on/off cycling of the compressor is a factor which will increase electricity consumption, mainly due to the large amount of energy required for the compressor to start. Compressor cycling can be a symptom of two of the factors illustrated in Figure 2, low heat loads or high flow temperatures. Cycling is also caused by behavioural practices such as window opening which causes relatively rapid loss of heat from the property. It can also be a result of heat pump controls being set to a narrow temperature range between start up and shut off (hysteresis setting). Short cycling can adversely affect the lifetime of the compressor and other components and has also been shown to result in reductions in system efficiency. Increased cycling is a symptom of initial poor specification or installation, or of ongoing poor operation due to knowledge gaps of the user and will have variable impacts on overall efficiency depending on the rate of the cycling. In addition, the spike in consumption when the compressor starts up increases demand on the grid which may require management as heat and transport are electrified.

Variable speed compressors (inverter driven) are designed to minimise this need for repeatedly switching on/off by adjusting the compressor speed to the required heat demand. Fixed speed compressors run at one speed which cannot be altered and turn on or off to meet heat demand. Good practice is to install a fixed speed compressor with a thermal buffer vessel to reduce cycling. There is conflicting evidence as to whether fixed or variable speed compressors offer higher efficiency, as well as conflicting opinions from heat pump manufacturers. There is also evidence that excessive cycling affects ASHP more than GSHP[47].

5.1.2 Building fabric

One source[48], which identified excessive compressor cycling caused by rapid temperature loss, associated this with building fabric issues, such as badly installed loft insulation or cavity wall insulation. Whilst building fabric insulation levels and airtightness have a direct impact on the system capacity requirements, it is less clear how building fabric affects the ratio of heat output to power input, and whether rapid temperature loss events can be attributed to it. More evidence is needed to understand this. The monitoring data from non-domestic RHI installations[49], and findings from a desk-based analysis of several European heat pump trials[50] show that building fabric has less impact on the heat pump performance than the other factors. A building with poor energy efficiency will have a higher heat demand, and therefore require a higher capacity heat pump. The occupier will therefore be impacted in terms of higher capital costs and electrical energy requirements (and therefore running costs), but the efficiency of the heat pump is not impacted by building fabric, as long as the initial sizing is accurate, and the appropriate sized heat pump and emitters are installed.

Whilst some data demonstrated that older, inefficient properties had lower performance, there is a lack of evidence to determine the cause of this. The higher flow temperatures required in uninsulated buildings will reduce the SCoP of a heat pump, but this can be managed by increasing the size of the heat emitters (see ‘Flow temperature’ below). Where the heat emitters are sized for lower temperatures, the SCoP will not be affected. Data from 28 non-domestic installations demonstrated that while less efficient buildings required higher output heat pumps (and so had higher electricity consumption), no impact on SCoP was found[51]. The key message is that the efficiency of a building does not have an impact on the SCoP, unless a higher flow temperature is required to meet the demand.

5.1.3 Flow temperature

Heat pumps operate most efficiently at low flow temperatures (see Table *2* for manufacturer’s example). However, at lower flow temperatures heat emitters transmit heat to rooms at a lower rate, meaning larger heat emitters are required to achieve thermal comfort. As the rate at which heat emitters are required to transfer heat into a room must match the rate at which heat escapes the room, the fabric efficiency of the building is also important for thermal comfort. Designing a heat pump system for optimal performance, therefore, involves a balance between flow temperatures, heat emitter sizing and fabric efficiency.

Heat emitters are the main determinant of flow temperature. Traditional wet heating systems are specified at higher flow temperatures than standard heat pumps, usually between 65 and 75ºC. This means, for a given level of fabric efficiency, heat emitters designed for use with a boiler will be too small for use with a heat pump. Large heat emitter surface areas can be achieved either by installing large radiators or by installing

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[47] UCL Energy Institute (2017) Investigating Variations in Performance of Heat Pumps Installed via the Renewable Heat Premium Payment (RHPP) Scheme

[48] Stafford, A. & Lilley, D (2012) Predicting in situ heat pump performance: An investigation into a single ground-source heat pump system in the context of 10 similar systems

[49] BEIS (2018) Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source & Water-Source Heat Pumps

[50] Gleeson, C. & Lowe, R. (2013) Meta-analysis of European heat pump field trial efficiencies

[51] BEIS (2018) Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source & Water-Source Heat Pumps

underfloor heating with closer loops. As the latter have a larger surface area they may be expected to accommodate lower flow temperatures, though the reviewed data does not actually demonstrate this. The RHPP field trial found examples of underfloor heating systems reaching maximum flow temperatures over 55ºC, and of properties with radiators operating with flow temperatures of 30 to 35ºC. The reasons for these differences could not be ascertained from the remotely monitored data. The RHPP report suggests that the underfloor heating systems recording high temperatures could be due to either mislabelling of the heating system in the metadata or poor design and/or installation.

Analysis of the RHPP trial data found that for ASHPs, there is some evidence that sites with underfloor heating have higher SCoPs than those with radiators. For GSHPs, those with underfloor heating appear to show a wider distribution in performance than those with radiators. The trial also demonstrated that overall, the relative performance of underfloor systems compared to those with radiators was not as different as may have been expected.

Wider variations in heat pump performance where underfloor heating is used could be attributed to the specification. As with radiators, increasing the surface area by installing more pipe loops closer together allows the system to run at a lower temperature. In addition, floor coverings above and insulation levels below the underfloor heating will also greatly affect the system flow temperature. None of the reviewed evidence made any reference to the underfloor heating specification.

A study of 10 GHSP installations[52] found evidence that temperatures were set too high by installers, who erred on the side of ensuring warmth for occupants, resulting in a higher flow temperature and lower CoP than would otherwise be the case.

In theory, control strategies such as operational timings and room temperature settings may impact flow temperature as heat pumps operated continuously should require lower flow temperatures. However, the RHPP field trial found that the difference in SPF between heat pumps operated continuously, with two heating periods, or only during the day was not statistically significant.

5.1.4 Load factor

The load factor is the heating demand met by the heat pump as a proportion of the heat pump capacity. Both a high load factor (undersizing) and low load factor (oversizing) can have a detrimental impact on the heat pump SCoP.

When considering the optimal sizing of a heat pump, there is guidance set by manufacturers and then for the UK by the MCS, with set internal temperatures and variable external temperatures based on the location. The set temperatures are designed to allow the heat pump to meet the heating requirements across the heating season for all but the rarest extreme weather. The design external temperature balances the need to provide heat efficiently during cold periods with the need to avoid oversizing the heat pump for warmer periods. Were the design external temperatures to be lower than current recommendations, then the heat pump would be oversized for the performance needed for a greater proportion of the year.

An oversized heat pump will have a low load factor, and this will lead to a low SCoP as system losses are proportionately higher, as are electrical loads for ancillary parts such as circulation pumps. Heat pump sizing is also affected by the calculated heat loss, which is sensitive to installer assumptions about ventilation and U-values. The same

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[52] Boait, P.J., Fan, D. & Stafford, A. (2011) Performance and control of domestic ground-source heat pumps in retrofit installations

issues apply for boiler sizing, but the running cost implications of oversizing boilers are lower in comparison.

Oversizing can also be attributed to over-cautious design, as is common with the specification of traditional heating systems. Oversizing is also possible in small properties as the minimum available capacity for most heat pumps in the UK is 5kW, which can be too much for the heat demand of small properties. Evidence suggests this has contributed to poor performance in some UK social housing retrofit heat pump schemes[53].

There are also behavioural and social factors which cause low heat demand, such as a desire to save energy or reduce high fuel bills. The use of supplementary forms of heating also results in a low load for the heat pump itself, and therefore lower performance. Detailed analysis of technical and social data from 21 case studies across the UK[54] found that user behaviours could often be attributed to factors such as the common perception that electric heating is expensive, and the perception that a heat pump could not sufficiently and/or simultaneously provide both heating and domestic hot water.

Where the load factor is high, due to an undersized heat pump, then the auxiliary heating will be in use more often, again reducing the SCoP. In addition, oversizing and undersizing the heat pump will have an impact on its lifespan, with the compressor either cycling too often (oversized) or running for too many hours (undersized).

5.1.5 Domestic hot water

Domestic hot water (DHW) is always supplied by a heat pump through an indirect cylinder, as the output flow temperature of a heat pump does not enable instantaneous production such as in a gas combi boiler. Therefore, due to the 55^{o}C maximum flow temperature of a standard heat pump, the cylinder must also incorporate an electric immersion heater to top up the temperature to the required 60^{o}C for legionella mitigation[55,56]. HHPs or high temperature heat pumps still require the indirect cylinder, but the immersion heater is for back up purposes only; the combustion part of the system provides the boost to hot water temperatures needed in these circumstances.

As the requirement for DHW to be heated beyond 60^{o}C is intermittent (one continual hour per day), DHW cylinders paired with heat pumps are specified to be larger than combustion systems to allow for lower stored water temperatures. Average shower output temperatures are around 43^{o}C, so a cylinder temperature of 50^{o}C is suitable if the volume is increased, allowing for the heat pump to provide most of the hot water demand and for the immersion to be used for legionella control only.

Heat pump CoP is impacted by the production of DHW, which requires higher temperatures than space heating, particularly outside of the heating season. Poor SCoP is associated with systems where a higher proportion of heat output is used for DHW.

Small properties, for example, will often have proportionally high demand for DHW in comparison to space heating. This leads to the overall system SCoP being poor, even if the space heating element is within acceptable levels. Monitoring data revealed that properties where DHW is provided by solar thermal systems or a separate immersion heater instead of the heat pump have much higher levels of heat pump SCoP. However, if the DHW is produced by a non-low carbon source, then the overall CO_2 emissions of

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[53] Boait, P.J., Fan, D. & Stafford, A. (2011) Performance and control of domestic ground-source heat pumps in retrofit installations

[54] UCL Energy Institute (2017) Case Studies Report from the RHPP Heat Pump Monitoring Campaign

[55] Building standards technical handbook 2020: domestic

[56] Health and Safety Executive (2014) Legionnaires' disease

the separated space heating and DHW will be higher. It is important to note that even what would be considered a low CoP (under 2.5) for DHW production from a heat pump it would still more efficient than using the immersion only (assumed efficiency of 99% - or equivalent CoP of 0.99).

Field trials (including the RHPP trials and InnovateUK project) found a periodic annual dip in CoP from June to August for ASHP systems. This was attributed to the decline in space heating demand which results in the heat pump only needing to meet hot water demand. This pattern in variations in CoP during summer is not as evident for GSHP systems.

5.1.6 System heat loss

Heat loss issues are primarily caused by poor insulation, or the location of the heat pump relative to the property. Of particular importance is the insulation of pipes, especially between the external unit and property, and the insulation of any hot water tanks located in the property. Any deviations from the optimal siting of an external unit are usually due to householder requests, for example locating ASHP units far from the property to reduce noise or perhaps for aesthetic reasons and tanks or immersion heaters in uninsulated garages or lofts. These heat loss issues could be improved if aesthetic and noise concerns can be overcome.

5.1.7 Resistance heating

The use of an internal boost function (inbuilt resistance heater) contained in some, but not all heat pumps, was identified as a cause of poor performance in several monitoring studies. Again, the onset of resistance heating could be triggered both by physical and behavioural factors such as under sizing of the heat pump, inaccurate set up or inappropriate user control. However, a particular theme emerged from the evidence of boost functions or immersion heaters switching on unintentionally and undetected by users, who were only alerted when they received unexpectedly high bills. Phase 2 of the EST trial demonstrated that the careful control of auxiliary electric heating on set up by the installer resulted in significant improvements in system efficiency. Occupants may benefit from feedback about which parts of the system impact operating efficiency, particularly auxiliary immersion heaters.

5.1.8 Excessive defrosting (ASHP only)

ASHPs can be affected by the build-up of frost on the outdoor heat exchanger. This reduces the efficiency of operation and for this reason ASHP have inbuilt defrost cycles. Defrosting can be achieved by hot gas defrosting, direct use of electric energy or temporarily reversing the heat pump flow. Excessive frosting and defrosting cycles can use significant amounts of electricity. One case in Phase 2 of the EST field trial (which monitored the energy used for defrosting) used as much as 14 kWh per day. While frosting happens when local outdoor temperatures are low, windspeed is low and humidity is high, evidence from Phase 2 of the EST trial found that the heat pumps with the greatest use of defrosting cycles were not located in the coldest parts of the country. This indicates other factors have a greater impact on the need for defrosting than low temperatures. In particular, frosting can be caused by limited airflow around external units, suggesting excessive defrosting is primarily a design issue rather than a reflection of variations in outdoor temperature across the UK. This suggests excessive defrosting should not be expected to be unusually significant in Scotland, provided external units are appropriately sited. Limited airflow can be caused both by poor initial design and by local changes (for example, a household putting large objects such as bins beside the heat collector).

5.1.9 External temperatures

Most heat pump models are able to extract ambient heat from source temperatures as low as -20ºC. This means heat pumps are suitable to providing heat in cold-winter countries, as is clear from their extensive use in Sweden. As the winter climate in Scotland is generally milder than Sweden's, outdoor temperatures do not represent a technical barrier to the use of heat pumps in Scotland. However, accounting for external temperatures is important both to correctly sizing a heat pump and to understanding how the electricity consumption of a heat pump varies across the heating season.

The CoP of a heat pump varies based on the temperature of the heat source, with colder incoming temperatures leading to lower CoP and warmer temperatures increasing the CoP relatively. As this is expected, the most used measure of performance is the SCoP, the annual average of the CoP.

The heat source of ASHP is more variable than for GSHP, meaning that ASHPs experience more of a fluctuation in CoP through the year, with the improved CoP in the shoulder seasons balanced out with reduced CoP during the winter.

Of the evidence reviewed, there was limited quantitative data on the impact of outdoor air temperature on CoP across groups of monitored ASHPs. However, as the SCoP figures are for the yearly average CoP, we can make assumptions that the maximum and minimum CoP range would straddle the SCoP for the heating season. Phase 2 of the EST trial found that ambient temperature has an impact on ASHP performance. The trial reported that a 15ºC increase in ambient temperature (-5 to 10ºC) was found to double ASHP system CoP. To illustrate, an ASHP operating across this temperature range with an SCoP of 3 would therefore see a variation of CoP between 2 (at cold temperatures) and 4 (at warm temperatures).

MCS guidelines for sizing ASHPs ensure the heat pump is able to fully meet the building's heat demand at all temperatures above a location-specific 'design external temperature'. The design external temperature balances the need to ensure a heat pump has capacity to operate efficiently during cold periods with the need to ensure it is not oversized (see 'Load factor' above). Design external temperatures represent particularly cold local conditions. For example, in the East of Scotland the design external temperature for sizing a ASHP output is -3.4ºC, whereas the average low temperature in Edinburgh for January is 3ºC. MCS guidelines also recommend forecast SCoP calculations incorporate design external temperatures to give a location-relevant prediction of running costs.

In-situ evidence of the impact of outdoor temperatures on GSHPs and WSHPs indicates a lower sensitivity of CoP. As the variation in heat source temperature is lower than ASHPs, these heat pumps should in theory show less variation in CoP across seasons. This was observed in Phase 2 of the EST field trials, and a study of 28 non-domestic GSHP and WSHP installations found that outdoor temperatures had no impact on heat pump performance in terms of the CoP[57]. In contrast, a study of 10 domestic GSHPs[58] reported that the CoPs dropped in colder spells and concluded that external temperatures were the primary driver of this. The apparent contradiction may reflect differences on the output rather than the input side of the heat pump, with the latter study possibly showing the effect of auxiliary heating (which could result either from an undersized heat pump or outdoor temperatures falling below design external temperatures). However, this was not recorded in the evidence.

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[57] BEIS (2018) Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source & Water-Source Heat Pumps

[58] Boait, P.J. et al. (2011) Performance and control of domestic ground-source heat pumps in retrofit installations

Two studies found that overall CoP also decreased during *warmer* periods[59,60]. The reason that the SCoP decreases over warmer periods when taking DHW provision into consideration can be attributed to the need for the heat pump to provide 55°C to the cylinder to create the DHW, and DHW becoming an increased percentage of the total demand on the heat pump. The intermittent higher flow temperature is then provided at a lower SCoP, rather than the continual lower flow temperature that optimises heat pump SCoP.

5.2 Identified measures to improve performance

This section considers how the performance of heat pumps can be maximised based on the causes of variations in heat pump performance identified above.

5.2.1 Knowledge gaps

Several sources suggested that observed ‘performance gaps’ may be better described as ‘knowledge gaps’ between manufacturers, installers and users. Knowledge gaps are evident throughout the process of system specification, commissioning, and handover to users. They result in false expectations as well as being a key driver in poor system performance. Measures to build knowledge and confidence in heat pump technologies, such as those in Sweden, Switzerland and Germany (section 8.4) could improve performance.

5.2.2 Specification and design

For small properties, manufacturers could be encouraged to produce units with capacity smaller than 5kW, to reduce instances of lightly loaded systems. However, consideration would need to be made on a case-by-case basis of whether a small capacity heat pump would justify the CAPEX compared to alternative electric heating.

The evidence suggests that rule-of-thumb methods are often used to facilitate heat pump design, for example the MCS Ground Heat Exchanger Look Up Tables to determine the total length of borehole heat exchangers. Rule-of-thumb design methods cannot provide optimal results and so targeted research is needed to understand this more clearly.

Users may benefit from system feedback or an alert to prevent unintentional use of auxiliary and immersion heaters. In the absence of a specific alert, inappropriate operation of auxiliary and immersion heaters may in some cases only come to the attention of users through unexpectedly high bills. Monitoring of heat pump systems can also help here.

No relationship has been found in the reviewed monitoring data between building fabric efficiency and heat pump performance. However, fabric efficiency is essential to specifying and sizing heat pump systems and heat emitters. In principle, this can have knock-on effects on performance, albeit the monitoring data reviewed is not suitable for testing this effect. For example, a poorly insulated property with a higher heat demand may not have space for the large low-temperature radiators required. Compromises on the size of the heat emitters installed to fit the available space can subsequently result in lower-than-expected performance.

In terms of DHW, there is a case for research projects to investigate alternative methods of controlling bacteria such as Legionella that are compatible with low temperature

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[59] Ibid.

[60] Energy Saving Trust & DECC (2013) Detailed analysis from the second phase of the Energy Saving Trust’s heat pump field trial

systems. If bacteria could be controlled without the need of increasing the temperature, then the heat pump efficiency would be improved.

For larger heat pumps, consideration must be made for thermal storage in the form of buffer vessels to manage the wider range in heat demand of larger buildings. In smaller properties with a lower heat demand range the demand on the heat pump is reduced, and so the benefits of a buffer vessel are negligible.

5.2.3 Installation

Heat pumps should be installed in accordance with MCS Standard MIS 3005. A best practice guide has been published by MCS and RECC[61] to support designers and installers to meet this standard and ensure optimum performance.

The installation stage determines both technical and user-behaviour reasons for variations in performance. The initial commissioning and selection of operation modes impacts flow temperature, compressor cycling, resistance heaters, and DHW. Poor performance can occur where actual commissioning settings do not match designer's intended control strategy or the control strategies of users e.g., a heat pump being set up to run continually and then a user setting the controls for intermittent heat. Commissioning and handover instructions are also key in shaping the control strategies of users.

Poor performance of heat pumps in the UK has been attributed to weaknesses in the vocational education and training (VET) available to installers[62]. Knowledge within the heating industry of heat loss calculations and domestic hot water sizing has become redundant due to gas combi boilers. However, professional knowledge on the part of the installer is essential if the high levels of sensitivity to the factors outlined in 5.1 are to be judged correctly. Such calculations are more important for heat pump installations than for gas boilers. There is a need therefore to improve installer competence in heat loss calculations. Improving installer knowledge, skills and wider competencies will be essential.

The set up and location of system components is also driven by user requests. Measures to improve consumer confidence in heat pump technology will help overcome the aesthetic and noise perception objections which can lead to poor location of heat pump units. In addition, EHPA suggest that more research is needed to determine whether the cause of vibration is in the design of the heat pumps or incorrect installation[63].

5.2.4 User behaviour

Advice for users could make a significant difference to the performance of heat pumps through heating control strategies. Participant surveys during the EST Phase 1 field trial revealed that higher system efficiencies were associated with greater user understanding of their heat pump system. This study also concluded that continuous heat pump operation led to greater efficiency, whereas the RHPP trial found that differences were not statistically significant. Current advice which advocates continuous operation for higher CoP values may not therefore be appropriate in all situations. Learnings from the BEIS Electrification of Heat trial may provide further evidence to clarify impact of heat pump operation.

The design and location of heat pump controls can improve performance through user behaviour. A simple measure is locating controllers where they are easily accessible.

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[61] MCS & RECC (2020) Domestic Heat Pumps: A Best Practice Guide

[62] Gleeson, C.P. (2015) Residential heat pump installations: the role of vocational education and training

[63] EHPA (2020) White Paper: Heat Pumps & Sound

The evidence provided examples of controllers located in hard to access lofts, cupboards, or facing a wall.

Controls should also be clear in terms of what they do. The EST Phase 2 trial found that users were unintentionally using auxiliary electric heating due to the settings being labelled ‘summer’ and ‘winter’. It was not clear that the winter setting activates the auxiliary electric heating. Controls must clearly indicate to the user whether the auxiliary heating or immersion is in use.

Smart heat pumps (see 8.2) allow automated control and remote monitoring of both performance and user control strategies.

5.2.5 Aftercare and maintenance

Two reports from the RHPP trial concluded that follow up visits may ensure that initial teething issues are resolved, and that performance is maintained over the long term. That 38 out of the 83 heat pumps in Phase 1 of the EST trial required further interventions demonstrates the importance of maintenance visits for identifying faults in the installation and setup of heat pump systems.

Maintenance packages (see 7.1) have also been recommended as a means of improving the customer experience. The provision of ongoing customer support through servicing regimes should be used to build consumer confidence in heat pumps.

5.2.6 Monitoring

Monitoring practices differed greatly across the evidence that we reviewed. Some registered social landlords (RSLs) have access to remote monitoring systems such as Melcloud, whereas other monitoring was based on comparing tenants’ bills before and after the installation and tenant surveys. Live and remote monitoring allows RSLs to directly identify faults or irregularities rather than relying on tenants to flag these.

There is evidence that monitoring can support improved performance. A study of six GSHPs in Germany[64] concluded that long-term monitoring of systems is needed to detect errors or inconsistencies affecting operation. Continuous monitoring and adjustment are necessary to ensure the intended operation of the system, particularly for commercial buildings or large blocks of flats such as in the German study. The long-term monitoring identified issues such as incorrect installation of valves, system components such a circulating pumps having been specified too small and poor control strategies. The study also highlighted, alongside monitoring, the importance of quality assurance during the construction phase, which can be generalised to all heat pump systems. There were also learnings specific to large-scale GSHP systems such as ensuring early integration of GSHP systems into building concept and control strategies.

Monitoring can improve broader understanding of performance, as well as issues for a user with a specific system. However, as one might expect, costs increase with levels of sophistication. In domestic systems, simple monitoring of the electricity consumption of components can be achieved using probes which measure electrical currents. This could alert engineers during servicing visits to inefficient operation if one component is using unexpected amounts of energy, which will assist with fault diagnostics.

More complex remote diagnostics can collect information on operation mode (heating/ cooling), flow data and heating performance. If abnormalities are detected, the monitoring platform will notify service providers and customers, providing possible causes. Modbus, a commonly used communication protocol for transmitting information, is open and currently the main compatible protocol for heat pumps. Some companies

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[64] Bockelmann, F. & Fisch, M.N. (2019) It Works - Long-Term Performance Measurement and Optimization of Six Ground Source Heat Pump Systems in Germany

have mentioned a poor real-time performance and low transmission rate which is hindering its widespread application. The high cost of the extra adaptor is also a barrier to uptake.

Monitoring of control strategies is required to determine the extent to which these are impacting performance.

5.3 Evidence gaps

As highlighted in Section 4.4, there is little evidence relating to the impact of construction type on heat pump performance. Small datasets from monitoring studies indicate that there is a wide variation of performance within the same property archetypes. Although there was very little reference in the evidence to the impact of building fabric on the SCoP of a heat pump, theoretically the SCoP of a heat pump would not be affected by the building fabric, as long as the correct size of heat emitter is installed. Building fabric determines heat loss values and heat demand which are used to specify heat pump and heat emitter size. Studies that did investigate this had small sample sizes, and the larger field trials we reviewed did not investigate impacts of fabric efficiency.

There was also a lack of conclusive evidence around the impact of buffer tanks on heat pump performance. Buffer tanks can be used to prevent short cycling, however there is limited evidence that this actually works. Phase 2 of the EST field trial found that buffer tanks did not seem to reduce cycling. The evidence shows that industry practice around the inclusion of buffer tanks varies considerably. There are also cost and space implications of installing buffer tanks. Further research is required to understand the operation of buffer tanks and to inform guidance for their use.

6 Less common heat pump technologies

This section provides a brief outline of less common heat pump technologies, both existing and proposed. For each technology we consider the relevant applications, the claimed advantages of these technologies over other types of heat pumps and whether any trade-offs exist in comparison to standard heat pump technologies.

The types of heat pumps listed below can each help to mitigate some of the traditional barriers to the uptake of heat pumps. For example, air-to-air systems remove the need for new wet heating systems in properties currently using electric heating. Hybrid and gas driven products may help overcome barriers associated with moving away from gas fired heating systems.

6.1 Air-to-air heat pumps

An air-to-air (A/A) heat pump is a reversible air conditioning unit which can provide heat. There are four types of A/A heat pumps, all of which can provide heating and cooling:

- Single split: Heats or cools the air in a single room. Consists of one indoor and one outdoor unit.
- Multi split: Consists of one outdoor unit connected to two or more indoor units. Each indoor unit has an individual refrigerant circuit.
- Variable Refrigerant Flow (VRF): One outdoor unit connected to one or more indoor units. Designed to adjust the flow of refrigerant to each indoor unit so that the heat delivered matches the demand, allowing different temperatures in different zones.

- VRF with heat recovery: As with VRF, controllers vary refrigerant flow to each indoor unit. The system can operate simultaneously in heating and/or cooling mode.

A report by Delta-EE[65] which assessed how A/A heat pumps are used in the residential sector in Europe detailed the following applications, advantages and trade-offs:

6.1.1 Application

Increased demand for cooling is driving growth in the A/A heat pump market in the UK. In Scotland there is potential for A/A heat pumps to replace electric storage heaters or direct electric heating in homes with no wet central heating system. The applications for A/A heat pumps are:

- Single split: Typically provides cooling to single rooms within the home, can provide heating to larger living areas (prevalent in Norway).
- Multi split: Typically provides cooling to a single larger indoor space, most commonly in the commercial sector. Less common in the residential sector as one single split can serve smaller rooms and multiple single split systems can be used to create different thermal zones.
- VRF: Popular in high end residential flats and commercial buildings.
- VRF with heat recovery: High end residential flats and commercial buildings.

6.1.2 Advantages

A/A heat pumps offer more energy efficient heating than direct electric appliances, without requiring the installation of a wet heating system. Key examples of its use are in France, Norway and Spain.

- Single split: Minimal disruption during installation.
- Multi split: All indoor units can be individually controlled.
- VRF: Allows increased number of indoor units per outdoor unit due to increased circuit length, thereby increasing the capacity of the system. Increases efficiency over a multi split by 11-17% by matching refrigerant flow to heating/cooling demand.
- VRF with heat recovery: Allows multiple thermal zones to be heated and/or cooled to different temperatures.

6.1.3 Trade-offs

- Single split: Cannot provide domestic hot water which then needs to be added such as direct electric or immersion heater in cylinder.
- Multi split: Requires an increased length of refrigerant piping with consequent disruption to building fabric compared to single splits, removing the benefit of not having to install a wet central heating system.
- VRF: Increased maintenance and costs compared to multi-split.
- VRF with heat recovery: Increased complexity and maintenance costs compared to VRF.

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[65] Delta-EE: Air/Air Heat Pumps: Characterising the European Residential Market

6.2 Communal heat pumps

A communal heat pump system can utilise any form of heat pump technology to provide heat to multiple properties.

6.2.1 Application

- Addressing multiple properties with a single heat pump can address some of the harder to treat property archetypes in Scotland.
- Cooling demand is often a driver for the installation of heat pumps over other heat sources in heat networks.
- Using heat pumps for both heating and cooling can help increase the efficiency of a system if heating and cooling loads are balanced.

6.2.2 Advantages

- Diversified demand, which can reduce impacts on the grid.
- Central control reduces risks of operational and management issues.
- Heat pump operation can be optimised by a scheme operator.
- Performance can be actively managed and there is less impact from occupants using systems in non-optimal ways.
- Reduces space requirement per property, so suitable where there are constraints such as flats.

6.2.3 Trade-offs

- The price of heat is likely to be significantly higher for heat networks incorporating heat pumps (compared to other heat network technologies such as CHP) due largely to the high capital cost of the heat pumps[66].
- The small number of operational heat pumps in heat network schemes in Scotland means that there is uncertainty around the heat pump performance that can be expected from such a system.

6.3 High-temperature heat pumps

High-temperature heat pumps are designed to provide a flow temperature similar to that of gas boilers. This allows for existing wet heating systems to be retrofitted with heat pumps without having to resize the existing radiators. There is a lack of in-situ data for retrofitted high temperature heat pumps in Scotland, or the rest of the UK. However, as some of the heat pumps being installed as part of the BEIS project are to be high temperature, this may generate some evidence.

6.3.1 Application

- Well suited to large, old, or listed properties due to high heat loss levels.
- Suited to properties with high, all year requirement for domestic hot water, particularly to replace the use of electric immersion heaters.
- Typically specified to heat large, old, or listed properties, often off the gas grid.

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[66] Changeworks (2017) District Heating: Delivering affordable and sustainable energy

6.3.2 Advantages

- Heat pumps can be retrofitted to high temperature distribution systems and can avoid the need for costly or disruptive upgrades to domestic heat distribution systems.
- More suited to producing domestic hot water than a standard heat pump due to increased flow temperature removing the need for an auxiliary immersion heater in the hot water cylinder.
- Could help overcome the consumer inertia which favours conventional gas boilers through the provision of high temperature space heating and domestic hot water outputs that customers expect[67].

6.3.3 Trade-offs

- As is explained above, heat pumps operate most efficiently with low flow temperatures. It is difficult to achieve high CoPs at high temperatures, with manufacturers data suggesting a SCoP of around 2.6 for a 65ºC design flow temperature versus 3.4 for a 55ºC flow temperature. So where possible installers may prefer to specify systems with lower flow temperatures even if it involves upgrading radiators.
- The price of high temperature heat pumps ranges from 20% to 35% more than standard heat pumps.
- Therefore, the performance of high temperature heat pumps is more sensitive to poor design, installation and operation than a standard heat pump.

6.4 Gas-driven heat pumps

Gas heat pumps are at a relatively early stage of deployment for domestic applications. Three gas-driven systems are currently available in the European market under two technology types: sorption (absorption and adsorption) heat pumps and gas engine-driven heat pumps. Sorption heat pumps use a thermal compressor to heat the refrigerant, whereas gas engine-driven heat pumps use a mechanical compressor (similar to electric heat pumps) but with gas as the energy source. Most gas-driven systems are air-to-air heat pumps, but they can also provide domestic hot water.

6.4.4 Application

- Gas absorption heat pumps: commonly used in commercial settings due to the size of available absorption products (generally >30kW). However, the introduction to the UK of an 18kW product in 2016 opened up the large domestic market. Suitable for retrofit or new build domestic properties on the gas grid.
- Gas adsorption heat pumps: suited to domestic properties due to size constraints(<15kW). Suitable for new build properties with low temperature heat distribution systems, as best operated at lower output temperatures (e.g., 40 to 45ºC).
- Gas engine driven heat pumps: Commercial buildings with a high demand for heating/cooling and long running hours. Unlikely to be used for smaller domestic properties in the short term.

6.4.5 Advantages

- Gas heat pumps reduce demand on the electricity grid, relieving capacity issues.

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[67] BEIS (2016) Evidence Gathering - Low Carbon Heating Technologies: Gas Driven Heat Pumps

- They can deliver cost savings compared to a standard electric heat pump, particularly where expensive and disruptive upgrades to the heat distribution system would otherwise be required. Radiator re-sizing is not required for absorption and gas driven heat pumps as they deliver relatively high temperatures (up to 65ºC), and efficiency does not fall as quickly at high temperatures compared with electric heat pumps. Gas driven products are likely to deliver a significant operational cost saving versus a new gas boiler and can deliver a carbon saving compared to a gas boiler.
- Consumer acceptance may be easier than for electric heat pumps as natural gas is a familiar fuel for domestic heating[68]. Currently gas heat pumps will also benefit from cheaper fuel at this time.

6.4.6 Trade-offs

- Limited performance data is available for domestic gas heat pumps. It is hard to draw conclusions on the relationship between test-condition and in-use performance. In the Heat4U trial of absorption heat pumps[69], the efficiency for space heating was 132% and for heating hot water was 128%. The calculated energy savings compared to a gas condensing boiler were 30%.
- There is very little training available for gas driven heat pumps except from manufacturers. However, sizing is not quite as critical as for electric heat pumps as gas engines usually have spare capacity.

The types of heat pump technologies listed above are intended to mitigate some of the barriers to the wider uptake of standard heat pumps. However, a key barrier of high upfront cost still exists for all technology types, alongside uncertainty on in-use savings. The current performance data available is based on laboratory conditions, and there is limited in-situ performance data available. Further evidence is needed on the in-situ performance of these types of heat pumps to understand ongoing costs, efficiency and user satisfaction.

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[68] BEIS (2016) Evidence Gathering - Low Carbon Heating Technologies: Gas Driven Heat Pumps

[69] Heat4U (2016) Gas Absorption Heat Pump solution for existing residential buildings

7 Servicing regimes, planning and grid requirements

This section details the evidence concerning servicing regimes, planning, and grid requirements of common heat pump technologies.

7.1 Servicing and maintenance

Heat pump maintenance is a key aspect of the consumer journey, and as outlined in section 5.2 is important for identifying faults in the installation and setup of heat pump systems. Most heat pump manufacturers recommend annual maintenance checks. Heat pumps usually require annual servicing to validate warranties, and it may also be a condition of certain schemes such as RHI. Annual servicing usually includes checking the outdoor unit is free of debris (ASHP), anti-freeze levels, refrigerant leaks and cleaning filters. An annual ASHP service typically costs £150-£240, whilst annual maintenance and breakdown packages can cost up to £450.

For example, Mitsubishi provide three levels of service. The most basic of these addresses just the heat pump, whilst the other service plans include the hot water cylinder. The basic heat pump service includes:

- cleaning the evaporator coil
- checking anti-freeze
- cleaning magnetic filters/strainers
- removing trapped air
- checking primary pressure
- checking flow rate and adjusting where possible/necessary
- checking controller settings and suitability

It is worth noting that other maintenance services do not include checking the suitability of controller settings. These servicing visits provide an opportunity to assess heat pump performance and make recommendations on settings and user control, although there is little evidence that this currently happens. Remote diagnostics can also help meet servicing and maintenance requirements. Providing the servicing engineer with data from the heat pump before undertaking the service allows for preparation and a focus on the required remedial actions.

7.2 Planning requirements

The two primary planning considerations for domestic installations are the noise and aesthetic impact of ASHP external fan units.

Domestic heat pump installations in Scotland are Permitted Developments (meaning their installation does not require planning permission applications). For GSHPs there are no restrictions on those permitted development rights, as long as the installation is within the property curtilage. For ASHP installations there are restrictions relating to the size and visual impact of external units.

ASHP installations must also comply with MCS Planning Standards[70]. These stipulate that noise levels for an ASHP on its own must stay at or below 42 decibels from a metre

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[70] MCS (2019) Planning Standards for Permitted Development Installations of Wind Turbines and Air Source Heat Pumps on Domestic Premises

distance away from any habitable room. If an installation does not meet the permitted development or MCS criteria, then planning permission is required from the local planning authority.

Some more expensive premium ASHP models with very low levels of noise can enable far more choice in the positioning of heat pumps. Likewise, careful positioning can mean that relatively noisier heat pumps are still able to meet noise requirements. Otherwise, solutions such as ground source or shared ground loops may be more suitable.

The NEDO project in Manchester conducted sound assessments in all properties and neighbouring properties. As part of the procedure for gaining planning approval for the installations in sheltered housing blocks of flats, the heat pumps had to meet the requirements set for noise levels in residential spaces. If more than one heat pump was installed in adjoining buildings, permitted noise levels may have been exceeded. Noise requirements are more difficult to meet in dense blocks of flats but careful choice of technology and placement to minimise sound pressure can resolve this across property types.

The requirements for non-domestic heat pumps are almost the same as for domestic installations. Heat collector pipework for non-domestic GSHPs must be less than 0.5 hectare, which avoids the need for an Environmental Impact Assessment.

7.3 Grid requirements

Based on load data from Delta-EE[71], it is estimated that by 2050 the electricity networks across Scotland will require substantial reinforcements as a result of the increase in electrical heat demand (from a range of electric heating systems including heat pumps).

The Low Carbon London project[72] measured consumption of 21 heat pumps to assess the network impacts. It found that the additional load at times of peak demand may cause thermal and voltage limits of infrastructure to be reached. Networks may have problems especially during extreme cold conditions when load diversity amongst different heat pumps in an area is reduced (due to reduced efficiency). Integrating large volumes of heat pumps could present a serious problem without adequate planning for and upgrading of networks. Findings from the Low Carbon London project showed that Distribution Network Operators (DNO) will need to continue to monitor the timing and uptake of both energy efficient appliances and new loads such as heat pumps and electric vehicles as they form their load forecasts.

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[71] Delta-EE and Smarter Grid Solutions (2016) Electrification of Heat and the Impact on the Scottish Electricity System:

[72] UKPN (2014) Low Carbon London Summary Report: DNO Guide to Future Smart Management of Distribution Networks

8 Innovation and development potential

This section outlines current innovations and developments in heat pump technology which are relevant to Scotland and focuses on those that would further improve heat pump performance.

8.1 Design and specification

Several developments have and are being made to improve heat pump technology including:

- **Specific products for coastal areas** that prevent corrosion from salt air after this was recognised as an issue in the 2000s. An example is the Mitsubishi coastal protection models.
- **Refrigerant improvements: t**here has been significant pressure on the heat pump market to develop alternative solutions to the current refrigerant options from the outcomes of the Kigali Agreement and the EU F-gas Regulations (relating to the global warming potential (GWP) of hydrofluorocarbons (HFCs)). The majority of European heat pump manufacturers now use R32 or R290 for their air-to-water heat pump portfolio[73]. There are claims of increased efficiency[74] although we were unable to find evidence of this in the in-situ trials.

In addition, the industry is identifying ways to improve the performance of heat pumps through more effective heat emitters. For example, the BEIS Electrification of Heat trial aims to include some systems with fan-assisted emitters to warm up the home more quickly.

The evidence shows that there is potential for innovation in the following areas to improve performance and satisfaction levels:

- **Domestic hot water: t**here is a case for research projects to investigate alternative methods or guidance for controlling bacteria such as Legionella. This would remove the need for regular sterilisation cycles which significantly impact performance.
- **Control: t**he most frequently identified cause of dissatisfaction among users relates to the control of heat pumps. The control panel itself seems to be very important in perceptions of user-friendliness. In the reviewed studies, participants were mostly moving to heat pumps from electric storage heating or direct electric heating. The dissatisfaction with controls is likely to reflect the differences between these types of heating systems.

8.2 Smart technology, tariffs and grid balancing

The energy system is currently undergoing a major transformation with increasing system flexibility, advances in ‘smart’ and connected technologies and a wider range of energy tariffs becoming available. This will inevitably have impacts on heat pumps by changing how and when they are operated and controlled, and how the electricity they

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[73] Delta-EE (2017) Refrigerants Round Up #5

[74] For example, in a survey undertaken by Delta-EE (2017) with heat pump and component manufacturers, almost three quarters of respondents believed that the new refrigerants would result in the same or greater efficiency levels.

run on is charged for. This could impact the pattern of heat pump usage by incentivising householders to use heat pumps at times of lower tariffs, potentially leading to lower running costs. It may also provide opportunities to participate in demand-side response if heat pumps are used alongside thermal stores or electric batteries.

8.2.1 Smart heat pumps

'Smart heat pumps' is a broad term covering a range of technologies. The three key functions of smart heat pumps are:

- Connectivity - to allow remote monitoring and control.
- Communication - of simple monitoring and status data, or signals from external sources such as weather forecasts and variable price signals.
- Control - ability to react to factors such as weather, and to learn from previous responses to proactively meet future demand.

At one end of the spectrum, a smart heat pump is simply about optimising the heating system within the home i.e., providing the required heat to the resident at an optimal cost. At the other end of the spectrum, a smart heat pump could be controlled externally to accept price signals or turn on/off/up/down to support the grid. In this regard, the heat pump provides demand-side flexibility whilst minimising impacts for the end user. Whilst this smart grid function is not currently used in the UK, most products sold within the UK are 'smart grid ready' i.e., the ability to accept signals from the DNO or a third party 'aggregator' managing the assets on their behalf.

The NEDO trial demonstrated that a group of heat pumps in the social housing sector can be utilised for demand response with very little impact on resident comfort levels, showing that if aggregated they could then be used for grid balancing services. The granularity of monitoring of data also enabled operational issues to be picked up quickly and resolved. A project on the Isles of Scilly demonstrated that smart heat pumps and thermal storage could be used to make better use of local energy generation whilst also reducing energy bills for consumers.

Smart controls will enable the use of hybrid heat pumps to significantly reduce the peak electricity demand compared to a standalone heat pump. Smart controls could respond to dynamic pricing or load control signals, as has been tested with hybrid heat pumps as part of the FREEDOM project.

8.2.2 Thermal energy storage

The demand for domestic heat storage to manage energy demand is likely to increase as the electrification of heat through heat pumps becomes more widespread. As many water cylinders in homes have been replaced with combi-boilers, creating new heat storage capacities in homes may be challenging. Two examples of solutions are heat storage products using phase-change materials in order to reduce its footprint in the home (e.g., Sunamp) as well as using heat pumps for instantaneous domestic hot water production, although this would have a negative impact on SCoP. The latter also removes the need for water sterilisation cycles, which as outlined in 5.1 can lead to lower performance.

Currently there are no empirical, user-centred studies of the heating and hot water provision that a householder might expect to receive from heat-pump with thermal storage system. However, one simulation[75] which tested different load-shifting methods (including E7 and E10 tariffs) suggests that space heating has a far higher sensitivity to

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[75] Marini, D., Buswell, R.A. & Hopfe, C.J. (2019) Sizing domestic air-source heat pump systems with thermal storage under varying electrical load shifting strategies

the load-shifting method than hot water provision. Sunamp batteries are being trialled as part of the BEIS Electrification of Heat project and are also being installed in conjunction with high temperature heat pumps by West Highland Housing Association[76].

Seasonal storage of heat is a promising technology for energy saving, but currently expensive in terms of capital costs in relation to the savings realised in operating costs. An example of this would be where excess heat from cooling during the summer season can be used to 'charge' the ground of a GSHP. The problem with seasonal storage is heat loss. Losses can be decreased by lowering the stored energy temperature. Storage can be combined with a heat pump as an efficient heating system to increase the stored energy temperature to the necessary level.

8.2.3 Electricity tariffs

Anecdotal evidence suggests some confusion around the best tariffs to use for heat pumps; for example, whether a single-rate tariff or dual rate (such as Economy 10) are most cost effective. This could have quite a major impact on the running costs of heat pumps.

Good Energy have recently released the UK's first heat pump tariff which offers a cheaper rate unit and rate reductions at specific times of the day.

An inevitable consequence of a smart grid is ever more complicated electricity tariffs such as dynamic time of use tariffs. This could be used by heat pump owners to benefit from cheaper rate tariffs at certain times of the day, potentially avoiding peak tariffs where suitably sized thermal or electrical storage is installed alongside the heat pump. There are however concerns that complex tariffs are unappealing to at least some consumers.

8.3 User acceptance issues

Whilst not impacting the performance of heat pumps, there are developments to heat pump products to improve customer appeal. This includes:

- Noise reduction: heat pump manufacturers are increasingly looking to reduce the noise of heat pump products. The 'quiet mark'[77] is an independent, international approval award programme to identify the quietest products and has been given to a number of heat pump products. Alternatively, acoustic enclosures can be used to reduce noise (e.g., Environ Acoustic Enclosures).
- Aesthetic improvements: the 'look' of an ASHP outdoor unit has sometimes been highlighted as a barrier to installation and this can be improved with solutions such as enclosures.

The BEIS Electrification of Heat demonstration project currently in progress includes noise abatement and aesthetic innovations to identify the extent to which they aid customer appeal. The findings from this will be of value.

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[76] Monitoring and evaluation is being conducted by Changeworks, but installations are ongoing at the time of this research.

[77] Quiet mark

8.4 Consumer confidence

Consumer confidence in heat pump technology is key in terms of user perceptions of performance. Research with customers across Europe[78] suggests that ongoing customer support is required throughout the customer journey e.g., pre-sale, installation, and after-sales stages. Several European countries, all with mature heat pump markets, have taken steps to build confidence among both installers and consumers through quality assurance and positive marketing[79].

A ‘heat pump court’ in Sweden was set up in 1989. The court is an independent complaints board which addresses litigation cases relating to the false claims of installers about heat pump performance. The court is run by the Swedish Heat Pump Association and allows customers to bring a claim directly against installers if heat pumps are perceived to underperform relative to expectations. The court has been essential in ensuring consumer confidence. About 60% of claims raised are usually won by the customer. In around 90% of cases, the problem is found to be with the installation rather than the heat pump technology[80]. Over-promising of heat pump performance by the installer has been identified as a common issue and is likely to result in perceptions of underperformance and dissatisfaction among consumers. A similar model in Scotland may improve installation quality control and consumer confidence.

The Swiss Government introduced a heat pump quality assurance programme to build confidence through independent testing of heat pump products and standardised installer training and certification for heat pump installations. The Swiss Federal Office of Energy started a Heat Pump Trial in 1996 to prove performance and demonstrate the potential of heat pumps. They are the longest-running heat pump trials in Europe and monitoring is still ongoing for some installations[81]. Results from this trial provided valuable data for customer engagement and are continuously fed back to the Heat Pump Association. Both Switzerland and Germany have had success with setting up a heat pump association to enable the delivery of quality assurance, marketing, and awareness-raising programmes. These were set up with Government support but are now market-led. The associations have participation from across the heating and energy industries including the energy industry, installers and contractors.

Although in the UK there is a the MCS Best Practice Guide for domestic heat pumps, it is focussed on design, sizing, specification and installation rather than consumer confidence or the customer journey where there is a lack of best practice standard in the UK.

9 Conclusions

There is not enough data on in-situ performance from Scotland alone, but when widening the research to include the rest of the UK, the evidence review suggests that heat pumps perform reasonably well in terms of efficiency, and in most cases, occupant satisfaction with heat pumps is high.

Heat pump performance is extremely sensitive to a number of factors, and therefore it is difficult to draw very clear conclusions on the precise relationship between expected performance or expected costs. However, the review found no evidence that these factors are likely to lead to lower heat pump performance in Scotland than in other

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[78] Delta- EE: European Customer Research High Efficiency Heating

[79] Delta-EE (2013) Report for Danish Energy Agency Policy - measures for heat pump market growth

[80] Ibid.

[81] Ibid.

countries where they are already common, including countries with colder winters such as Sweden. Poor heat pump performance is most likely to arise due to poor design and specification, rather than resulting from any aspect of the Scottish climate or building stock; this means appropriate design and installation are the most important considerations to ensuring heat pumps perform well in Scotland.

Performance

The review of heat pump field trials and monitoring data revealed a wide performance range in terms of SCoP. This kind of performance data cannot easily be compared between trials due to the use of different system boundaries, or system boundaries not being clearly defined.

Running costs are a key outcome for occupant satisfaction with heat pumps. In many studies they were not used as a performance metric. Running costs are context specific and depend on a number of variables including electricity tariff, user behaviour and correct specification of heat pump and heat emitter capacity.

Based on the UK trials reviewed, performance in terms of user satisfaction was generally high. The evidence we reviewed demonstrates complex feedback loops between heat pump performance, levels of satisfaction and user behaviour. From this data, the most frequently identified cause of dissatisfaction among occupants relates to the control of heat pumps. Controlling inbuilt auxiliary boost heaters seems to be a particular issue as this can go undetected until occupants receive unexpectedly high bills. Advances in ‘smart’ and connected heat pump technologies are expected to have significant impacts for user operation and control. But further research would be required to determine the scale of impact.

Variations in performance

The evidence examined in this review reveals that heat pump systems are sensitive to design, installation, and user behaviours in ways that gas, oil and electric resistance heating are not.

We found that variations in heat pump performance were mostly a result of system loads, flow temperatures, system demand for DHW, and excessive compressor cycling. These immediate causes within the heat pump systems are a result of a complex web of behavioural, social, and technical factors. For example, an inappropriately located ASHP may result in heat loss and excessive defrosting, leading to poor performance. The location may be a result of poor installation practice, or due to customer preferences. Such preferences are influenced by noise and aesthetic concerns. However, we also found examples of mitigation activities that might address this range of concerns.

Consumer confidence, satisfaction and the customer journey are closely linked, and influence user behaviours. Examples of poor performance have been linked to behaviours such as using auxiliary heaters. This can be due to a lack of trust and confidence in the ability of a heat pump system to provide adequate heat.

For optimum performance, the design, specification and commissioning of heat pumps needs to be done on a bespoke basis per property. Although more evidence is needed, the review suggests correct specification and sizing of heat pumps and heat emitters are critical determinants of heat pump performance.

Hybrid heat pumps

HHPs have the potential to significantly reduce the peak electricity demand compared to a standalone heat pump. However, the reviewed evidence showed that the share of heat demand met by the heat pump element varied from 1% to 96% depending on the specification and consumer behaviours. To meet grid balancing and decarbonisation objectives, parameters need to be set to determine how and when HHP systems make use of the heat pump and boiler components. Smart controllers will be a key enabler of this.

Gaps in current evidence

This research has identified several gaps in the data. There are few large-scale datasets specific to Scotland, its building stock and climate. In particular, there is a significant lack of data from trials where heat pumps have replaced natural gas heating. This means that there is a lack of data on: how consumers, who are used to natural gas central heating, will respond to heat pumps; differences in running costs between the systems; and how efficiently heat pumps operate when retrofitted to existing wet heating systems. We believe this gap will be addressed by findings from the ongoing BEIS Electrification of Heat trial, which will also hopefully address the lack of monitoring data for high temperature heat pumps.

The data we reviewed did not suggest any issues specific to Scotland should lead to an expectation of heat pump performance being below that achievable in other countries. In relation to several specific second-order questions, the data was inconclusive. We were unable to find data showing: the seasonal variation in electricity consumption with outdoor temperatures; the quantitative relationship between SCoPs and construction types or building fabric; or the impacts of using buffer tanks on SCoP or heat pump cycling. We could not assess the relative impact these three issues may have on performance.

The research has also revealed that the quality of monitoring practices and, subsequently, data varies widely. During the evidence search we found that a large number of monitoring studies were using estimated heat output figures rather than metered heat output. Where heat meters are being used there is evidence of incorrect placement or poor choice of sensors, which impacts data quality and reliability.

Appendix 1: Evidence Base

Organisation / Author	Date	Title	Geography
BEIS	2016	Evidence Gathering – Low Carbon Heating Technologies: Domestic High Temperature, Hybrid and Gas Driven Heat Pumps: Summary Report	UK
BEIS	2016	Evidence Gathering – Low Carbon Heating Technologies: Gas Driven Heat Pumps	UK
BEIS	2018	Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source & Water-Source Heat Pumps	UK
Boait, P.J., Fan, D. & Stafford, A	2011	Performance and control of domestic ground-source heat pumps in retrofit installations	England
Caird, S., Roy, R. & Potter, S.	2012	Domestic heat pumps in the UK: user behaviour, satisfaction and performance	UK
Carroll, P., Chesser, M. & Lyons, P.	2020	Air Source Heat Pumps field studies: A systematic literature review	Ireland
Citizens Advice Scotland (CAS)	2016	Hot off the Grid	Scotland
ClimateXChange	2020	Public awareness of and attitudes to low-carbon heating technologies	Scotland
Consumer Focus Scotland	2012	21st century heating in rural homes	Scotland
De Montfort University	2017	Monitoring data from a housing provider in the East Midlands	England
Delta-EE	2013	Report for Danish Energy Agency on Policy measures for heat pump market growth	Europe wide
Delta-EE	2020	Remote Diagnostics Service 2020 Connected Home Service	Europe wide
Delta-EE		European Customer Research High Efficiency Heating	Europe wide
Delta-EE		Air/Air Heat Pumps - Characterising the European Residential Market	Europe wide
Element Energy	2017	Hybrid heat pumps	UK
Element Energy and Carbon Alternatives	2016	Heat pumps in district heating	UK
Energy Saving Trust & DECC	2012	Detailed analysis from the first phase of the Energy Saving Trust’s heat pump field trial	UK
Energy Saving Trust & DECC	2013	Detailed analysis from the second phase of the Energy Saving Trust’s heat pump field trial	UK
European Heat Pump Association (EHPA)	2020	White paper: heat pumps & sound	UK
Gleeson, C.P.	2015	Residential heat pump installations: the role of vocational education and training	UK
Gleeson, C.P. & Lowe, R.	2013	Meta-analysis of European heat pump field trial efficiencies	European trials

Organisation / Author	Date	Title	Geography
Greater Manchester Combined Authority and NEDO	2014	Greater Manchester Smart Community Demonstration Project	UK
Hebridean Housing Partnership	2020	Monitoring data from 17 ASHPs	Scotland
Hitachi, Moixa, PassivSystems	2020	Smart Energy Islands	UK
Hjaltland Housing Association	2011-2019	Hjaltland HA Tenant Feedback data	Scotland
International Energy Agency	2014	Quality Installation / Quality Maintenance Sensitivity Studies (Avoiding Heat Pump Efficiency Degradation Due to Poor Installations and Maintenance)	France, Sweden, UK, USA
James Hutton Institute & Orkney Housing Association Ltd	2014	Heat Pump Survey Year 1	Scotland
James Hutton Institute & Orkney Housing Association Ltd	2015	Heat Pump Survey Year 2	Scotland
Littlewood, J.R. & Smallwood, I.	2017	One Year Temperature and Heat Pump Performance for a Micro- Community of low Carbon Dwellings, in Wales, UK	Wales
Ma, Z., Xia, L., Gong, X., Kokogiannakis, G., Wang, S. & Zhou, X.	2020	Recent advances and development in optimal design and control of ground source heat pump systems	Australia
Marini, D., Buswell, R.A. & Hopfe, C.J.	2019	Sizing domestic air-source heat pump systems with thermal storage under varying electrical load shifting strategies	UK
National Energy Action	2017	Daikin Altherma hybrid heat pumps, Copeland and South Tyneside (CP747)	England
National Energy Action	2017	Heat pumps for park homes, Basingstoke YES Energy Solutions (CP753)	England
National Energy Action	2018	Replacing gas boilers with Daikin Altherma hybrid heat pumps (CP759)	England
National Energy Action	2018	Air-source heat pumps, solar PVT and heat recovery in off-gas homes (CP752)	England
National Energy Action	2018	Ground-source heat pumps in sheltered housing – Bromley (CP746)	England
National Energy Action	2019	Gas Absorption Heat Pump for a Sheltered Housing Scheme Colchester Borough Homes (CP742)	England
National Energy Action	2019	Mitsubishi Ecodan Hybrid heat pumps with existing oil/boiler system (CP786)	England
RECC	2018	Background to Heat Pump Seasonal Coefficient of Performance (SCOP) metric and an analysis of its use.	UK
RECC	2020	RECC Analysis of Ofgem ‘Metering for Payment’ Data	UK

Organisation / Author	Date	Title	Geography
Rees, S. & Curtis, R.	2014	National Deployment of Domestic Geothermal Heat Pump Technology: Observations on the UK Experience 1995–2013	England
Shah, N.N., Wilson, C., Huang, M.J. & Hewitt, N.J.	2018	Analysis on field trial of high temperature heat pump integrated with thermal energy storage in domestic retrofit installation	Northern Ireland
Stafford, A. & Lilley, D.	2012	Predicting in-situ heat pump performance: An investigation into a single ground-source heat pump system in the context of 10 similar systems	England
Steinbeis-Innovationszentrum	2019	It Works: Long-Term Performance Measurement and Optimization of Six Ground Source Heat Pump Systems in Germany	Germany
Sun, M., Djapic, P., Aunedi, M., Pudjianto, D. & Strbac, G.	2019	Benefits of smart control of hybrid heat pumps: An analysis of field trial data	England
The Carbon Trust	2020	Heat pump retrofit in London	UK
UCL Energy Institute	2017	Investigating Variations in Performance of Heat Pumps Installed Via the Renewable Heat Premium Payment (RHPP) Scheme	UK
UCL Energy Institute	2017	Case Studies Report from the RHPP Heat Pump Monitoring Campaign	UK
UCL Energy Institute	2017	Analysis of Heat Pump data from the Renewable Heat Premium Payment Scheme (RHPP): Compliance with MCS Installation Standards.	UK
UK Power Networks & Low Carbon London Learning Lab	2014	DNO Guide to Future Smart Management of Distribution Networks Summary Report	UK
Western Power Distribution and Wales & West Utilities	2019	Freedom Project report	UK

Appendix 2: Research methodology

The evidence reviewed for this report was a combination of grey literature, published research, academic papers, and case studies[82] covering the UK and international comparisons. For in-situ evidence of how heat pumps are likely to perform in Scotland we reviewed both large-scale heat pump field trials, and small-scale monitoring studies. Monitoring data from small-scale studies was also included in the evidence review. This includes data from housing providers, other stakeholder organisations and results from academic papers which used in-situ data.

A2.1 Scoping

The research team formulated specific research questions and sub-questions which addressed the aims and cross-cutting themes of this research. We produced a research framework to structure the direction, topics and prioritisation of research objectives.

The research framework contained the following research question, in order of prioritisation:

1. **How do heat pumps perform in-situ in Scotland or in other countries, in terms of running cost, consumption, satisfaction or efficiency?**
    - **a.** What is the current state of evidence for how heat pumps perform in-situ in Scottish buildings? What is the extent and quality of data, and what gaps are there?
    - **b.** How does performance vary by property type, and in particular types of housing prevalent in Scotland?
    - **c.** How does performance vary by climatic locations/conditions (including humidity), particularly during cold periods?
2. **What are the causes of variations in performance of heat pumps at the specification and system design stage?**
    - **a.** What can be done to maximise performance at during specification and design?
    - **b.** What impact do heat emitters and energy efficiency levels/housing fabric have on heat pump performance?
3. **What factors at the installation stage can lead to variations in performance?**
    - **a.** What measures can be put in place at installation to maximise heat pump performance?
    - **b.** What can go wrong at the installation stage resulting in performance issues?
    - **c.** What evidence is there that installer accreditation and skillset impacts heat pump performance?
    - **d.** What evidence is there from installers' perspectives on these issues?
4. **What behavioural factors can impact heat pump performance?**
    - **a.** What are the interactions between user behaviour and heat pump performance?

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[82] A full list of studies can be found in appendix 1.

   - **b.** Under what circumstances / how often are auxiliary heaters used in buildings with heat pumps?

5. **What impact do aftercare and maintenance have on heat pump performance?**
   - **a.** How can servicing and maintenance regimes be used to maximise heat pump performance?
   - **b.** What evidence is there that monitoring can support improved performance?
6. **Are there practical or other factors that impact heat pump performance that are of relevance to Scottish circumstances?**
7. **What factors are of particular relevance to Scottish housing stock, such as pre-1919 tenements?**
   - **a.** Are there other factors specific to Scotland that need to be taken into consideration? E.g., electric network constraints. *(This question will be addressed on a high level given the research scope)*
8. **How do 'less common' heat pump technologies perform, both in Scotland and comparable countries?**
   - **a.** What are the claimed advantages of these technologies over other types of heat pumps? Is there evidence for this?
   - **b.** What are the applications of these heat pump types, for example, housing types?
   - **c.** What are the common technical barriers to the installation of 'standard' heat pumps?
   - **d.** How, and to what extent, do 'less common' technologies overcome these barriers?
   - **e.** What trade-offs exist with the installation of different types of heat pumps? For example, cost of installation vs. running costs.
9. **What are the steps of the consumer journey from pre-installation to operation?**
   - **a.** How does the journey differ between different types of consumers (e.g., social / private housing, accessing Government support)?
   - **b.** What evidence is there of the impact of the consumer journey on satisfaction or experience of heat pumps?
10. **What are the required servicing regimes, planning and grid requirements of common heat pump technologies?**
    - **a.** What evidence is there that these factors are barriers to heat pump uptake in Scotland?
11. **What examples of best practice are there in relation to heat pump performance?**
    - **a.** specification
    - **b.** installation
    - **c.** user support
    - **d.** Government support/organisations/schemes set up to aid improved performance.

12. **Where is there room for innovation and development in Scotland that would further improve performance? Consider:**
    - **a.** Refrigerants
    - **b.** Seasonal Performance Factor & Coefficient of Performance
    - **c.** User behaviour
    - **d.** Larger scale heat pumps
    - **e.** Higher output temperatures
    - **f.** Suitable electricity tariff structures
13. **Where are there gaps in the evidence available?**
    - **a.** Where is there conflicting evidence?
14. **What recent improvements have there been in heat pump technology in terms of design, installation and efficiency, ability to meet entire household space heating and hot water provision?**

In recognition of the lack of published monitoring data for heat pumps, the research team made contact with a number of stakeholders which may have unpublished heat pump data. This included heat pump manufacturers, housing associations, local authorities, Local Energy Scotland (LES), Renewable Energy Consumer Code (RECC), National Energy Action (NEA), Scottish Federation of Housing Associations (SFHA), Citizens Advice Scotland (CAS), as well as UK trials such as the FREEDOM project and Greater Manchester NEDO project.

A2.2 Identification of evidence

Based on the research questions the research team developed inclusion and exclusion criteria and search terms to guide the evidence search. The search consisted of an internal evidence review of Delta-EE's extensive private publications and research on heat pumps, as well as a web search of grey literature, published research, academic papers, and case studies using both Google and Science Direct search engines. Further evidence was identified through reference mining of identified evidence sources.

The following search terms were used to identify sources:

Table 4: List of search terms

heat pump	field trial	frost
Perform	COP	quality
performance	SPF	installation
in-situ	cold weather	maintenance
Monitor	performance analysis	effect
Efficiency	thermal comfort	servicing
Data	feedback loop	optimise
running cost	measure	thermal storage
Domestic	interaction	buffer
Retrofit	climate	
consumption	humidity	

A2.3 Sifting of evidence

The research team read abstracts (or similar) from the identified evidence and screened it against the agreed inclusion / exclusion criteria.

- Only in-situ performance data was included (modelled data or studies in laboratory conditions were excluded)
- UK field trials which took place prior to the introduction of MCS in 2010 were excluded.
- Data were included from non-UK studies set in countries with comparable climatic conditions to Scottish (temperate maritime conditions).

Following this exclusion process, each piece of evidence was described and mapped against the research questions. This process ensured that each piece of evidence we reviewed was relevant to the research, and clearly demonstrated where there are gaps in the evidence. The evidence map was also used to appraise the evidence, with each piece of evidence assigned a score for its quality and relevance to the research.

Quality and relevance of the evidence sources were assessed based on the following:

Table 5: Quality and relevance criteria

Quality Criteria	Relevance Criteria
Sample size	Climate similar to Scotland
Perceived bias	Property type similar to Scotland
Robustness of method	Data from retrofitted heat pumps were prioritised over new builds
	COP calculations based on heat meter readings were prioritised

At this stage further evidence sources were excluded from the research based on factors such as sample size, quality and relevance. The final evidence base consisted of 51 sources, as listed in Appendix 1.

A2.4 Review and analysis

Key findings from each evidence source were recorded in the table. The research team then synthesised the findings from the table into narrative form. As well as drawing results together, this also involved highlighting where there was insufficient evidence against research questions posed.

Appendix 3 - Heat Pump Operation

A3.1 How heat pumps work

Heat pumps are an established technology based on the refrigeration cycle developed in the 19th century and first used for space heating in the 2000s. Smaller domestic-scale models have been installed since the 1970s, with the current drive for the decarbonisation of heat increasing demand.

A heat pump operates by capturing the latent heat in the air, ground or water and passing it through a heat exchanger. On the other side of the heat exchanger is a refrigerant which when heated by the source is vapourised. The vapour is then compressed, which raises the temperature of the refrigerant before passing through a second heat exchanger. At this higher temperature the heat can be transferred to the water in the distribution system before flowing through the heat emitters and an indirect coil in a cylinder for domestic hot water provision.

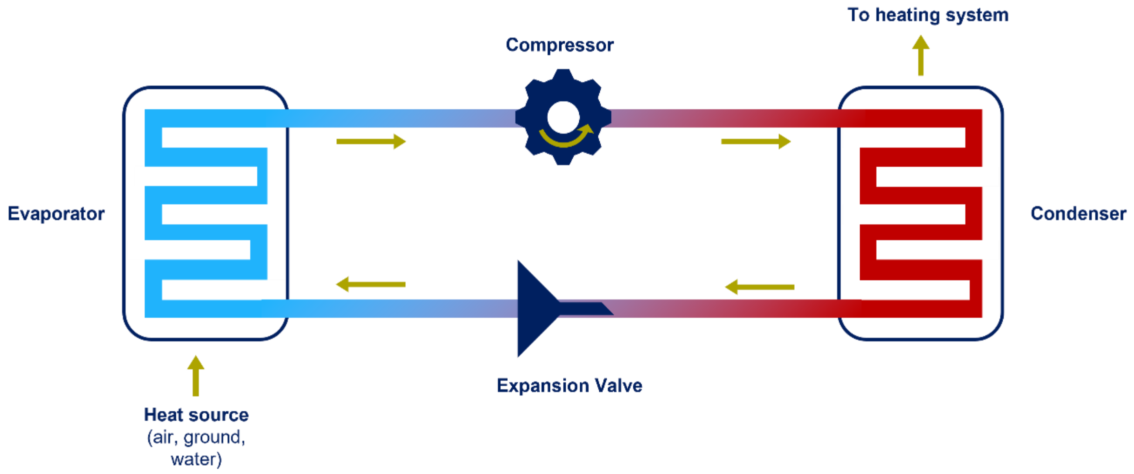

Figure 3: Diagram of a heat pump. The main components of a heat pump are an evaporator, a compressor, a condenser and an expansion valve.

The temperature of the source can be below freezing point, with most manufacturers stating minimum operating temperatures of around -20ºC. As long as the refrigerant is cooler than the source it will pick up the latent heat. Most commercially available heat pumps are designed for low temperature heating, with the maximum flow temperature being 55ºC. High temperature heat pumps use either a direct electrical element to raise the flow temperature up to 75ºC, or uses two heat pumps in series, with the heat output from the first being the input to the second.

Air, ground and water source heat pumps are an established heating technology in other European countries, such as Sweden. Due to financial incentives such as RHI, and minimum efficiency requirements for new builds heat pumps have become more common as a space heating solution in Scotland, although exact install figures are unknown. The total installed number is however still low, with figures from 2019 showing that less than 1% of the UK housing stock (250,000 homes) are heated by a heat pump[83]. The increase in their uptake has led to improvements in the technical

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[83] Energy Saving Trust (2019) The future of heating in the UK

specification as well as the aesthetics of heat pumps to adapt and appeal to the consumer market.

Table 6 gives a brief overview of the different types of heat pumps referred to in this report and their characteristics.

Table 6: Table of the different types of heat pumps referred to in this report

Heat pump type	Brief description	Heat source	Examples of heat collectors	Heating medium	Heat Emitters
Air Source Heat Pump	Transfers heat from ambient air to a higher temperature	Air	Fan	Water	Wet heating system (radiators or underfloor heating)
Ground Source Heat Pump	Transfers heat from the ground to a higher temperature	Ground	Borehole or ground loop	Water	Wet heating system (radiators or underfloor heating)
Water Source Heat Pump	Transfers heat from water source to a higher temperature	Water	Pond mats, open loop boreholes or straight pipe collectors	Water	Wet heating system (radiators or underfloor heating)
Air to Air Heat Pump	A reversible air conditioning unit which can provide heat	Air	Fan	Air	Fan convection heater
Exhaust Air Heat Pump	Transfers heat from exhaust air to a higher temperature	Exhaust air of a building	Fan	Water	Wet heating system (radiators or underfloor heating)
Gas Absorption Heat Pump	Uses a thermal compressor instead of a mechanical compressor	Air, ground, or water	Any of the above	Water	Wet heating system (radiators or underfloor heating)
Gas Engine Driven Heat Pump	The mechanical compressor is powered by gas instead of electricity	Air	Fan	Air	Fan convection heater
Low Temperature Heat Pump	Can provide water flow temperatures of up to 55°C.	Air, ground, or water	Any of the above	Water	Wet heating system (radiators or underfloor heating)
High Temperature Heat Pump	Provide a flow temperature similar to that of gas boilers. Should only be considered where low temperature heat pumps are not feasible.	Air, ground, or water	Any of the above	Water	Wet heating system (radiators or underfloor heating)
Hybrid Heat Pump	A hybrid system combines any type of heat pump with any form of combustion heating.	Air, ground, or water	Any of the above	Water	Any of the above

Hybrid heat pumps

Hybrid heat pumps are the combination of a heat pump with a combustion heating system, either as a single packaged unit or bivalent with each system installed separately. A hybrid heat pump system can meet the full heating and hot water needs of a domestic property. The boiler is used to reach the higher temperatures needed to provide domestic hot water, whilst the heat pump can provide base load low temperature heating at a lower cost and using less energy. The share of heat demand met by the heat pump element of hybrid systems is completely variable.

Generally, SCoP of the heat pump element is higher than monovalent systems, although this is attributed to the combustion element of the system providing heating during colder periods. The efficiency of the overall HHP system is highly dependent on the operating mode. Parallel operation (boiler and heat pump working together instead of one at a time) is associated with higher levels of performance.

A3.2 System flow temperatures

The key differences between a heat pump and a traditional combustion heating system such as a gas boiler (Table 77) lies primarily in the operation and flow temperatures. Where a gas boiler will produce a flow temperature of between 60 and 80°C instantaneously, the mechanics of a stand-alone low temperature heat pump take longer to achieve its target flow temperature of up to 55°C. Therefore, if heating a building from cold it will take longer to achieve the target internal temperatures with a heat pump. A high temperature heat pump will operate in the same manner, but can achieve a higher final temperature where required, up to 75°C. Due to the time lag in achieving the target internal temperatures, heat pumps are recommended to be set to continual operation, with the internal temperatures increasing and decreasing based on occupier preference.

Table 7: Key differences between heating systems.

Heating technology	Efficiency range	Operational mode	Flow temperature
Combustion system (gas, oil, LPG as fuel)	Up to 92%	Intermittent	~ 75°C design temperature but can operate up to 90°C
Heat pump (air, ground or water source)	180 – 450% (SCoP 1.8-4.5)	Continual	Max. 55°C low temperature heat pump, Max 75°C high temperature heat pump

There are several ways to increase the flow temperature of a heat pump, such as direct electrical elements or secondary compressors used in high temperature heat pumps or pairing the heat pump with a combustion system (referred to as a hybrid).

The introduction of either additional electrical energy from direct electrical elements or heat from a non-renewable combustion system can reduce the overall performance to below a standard that would allow the system to be classed as renewable, which is defined as a SCoP of 2.5 or above[84].

Where the lower flow temperature of a heat pump in comparison to combustion systems has most impact is in the heat emitter specification. Traditional combustion boiler's heat emitters are specified based on the flow temperature being 50°C higher than the set internal room temperature to meet the calculated heat demand, which usually results in

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[84] The European Parliament and the Council of the European Union (2009) EU Renewable Energy Directive

a flow temperature of around 75ºC. A heat pump's emitters are specified at as low a flow temperature as possible, from as low as 30ºC up to 55ºC. This can create a need to significantly increase the size of the heat emitters such as radiators or use underfloor heating. Specifically, in certain retrofit scenarios where rooms have limited wall space or floor space for underfloor heating this can result in the heat emitter requirement not being logistically possible. Typically, a radiator sized for a heat pump's lower flow temperature would be at least twice the surface area of a radiators sized for a combustion system. Although the radiators can be double or triple panel, or potentially vertical, some properties still may not have enough space, or the costs would be prohibitive for heat pumps. We did not find data to identify the relevant number of properties.

Hot water provision is also affected by the lower flow temperatures of heat pumps. As heat pumps are unable to provide instantaneous hot water there is always a requirement for an indirect hot water cylinder. The cylinder requires a coil inside, which has the heated water from the heat pump running through it to indirectly heat the potable water contained within the cylinder. Compared with a hot water cylinder fed by a boiler, the coil needs to have a larger surface area to allow for adequate heat transfer at the lower temperature. The cylinder itself also needs to have an increased volume to meet the domestic hot water demand of the property. This is because the flow temperature from a combustion system is higher than that of a heat pump. The stored water temperature is therefore also higher.

Building control regulations require domestic hot water to be heated above 60ºC intermittently to prevent the risk of legionella bacteria forming, this is almost exclusively done with direct electrical elements within the cylinder, known as immersion heaters. The use of auxiliary electrical elements, and the frequency of their operation, has a negative impact on the overall heat pump SCoP if included in the monitoring system boundary. The degree of this impact is variable dependent on the operational settings.

A traditional combustion system operates in an 'on/off' mode, where the boiler is either producing heat quickly or switched off entirely until called on again. This then allows for a user to choose to turn the heating on with a rapid heat up time. The heating cycle of the heat pump is a more gradual process and so operates by maintaining a relatively constant level of heat required as set by an internal programmable thermostat. This alteration in the heat provision from a heat pump requires the end user to adapt their behaviour, for example, adapting to their home having the temperature maintained continually, or warming up over a longer period than a combustion system can achieve if the heating system is switched off. This can sometimes be at odds with consumer expectations, and this lack of understanding when combined with maintaining old habits from a combustion system will have an impact on the heat pump performance.

A3.3 External temperatures

MCS guidelines for sizing ASHPs ensure that the heat pump is able to fully meet the building's heat demand at all temperatures above a location-specific 'design external temperature'. Below the design temperature, the heat pump will still produce heat, with most models operating down to -20ºC.

A rare weather event, where temperatures fall below the design for more than a short period of time, will result in designed internal temperatures not being met by the heat pump alone. In some heat pumps an auxiliary electrical element may be built in. This will activate during periods colder than the design external temperatures to maintain internal comfort. However, where the heat pump does not have auxiliary heating, there will be a drop in internal temperature.

As the design internal temperatures are assuming every room in the building is heated to between 18 and 21ºC dependant on the room use, comfort can be managed by reducing the target temperature in vacant rooms. It is important to note that these are the same conditions for any heating system, and also that any heat emitter will struggle to achieve a design room temperature if the external temperature is below the initial sizing specifications.

Low outdoor temperatures increase the heat needed by a building to keep warm. When using a boiler or electric storage heating, this means the rate at which energy is consumed increases in cold weather. A building using an ASHP likewise requires a higher rate of energy delivered by the heat pump, but the increase in electricity consumption is then exacerbated by the lower CoP. This concentrates electricity consumption (and hence running costs) of an ASHP in cold periods to a greater degree than other heating systems. This is a well-recognised aspect of heat pump functioning, common to heat pumps that operate effectively in colder climates than Scotland's, and is encapsulated in the use of the SCoP measure. It underscores the importance of good design to ensure periods of high electricity consumption are balanced by periods of lower consumption during warm weather.

While there is no evidence to indicate the effect is particularly significant in the Scottish climate, the relative concentration of annual electricity consumption during cold periods may create specific challenges for consumers on pre-payment meters switching to heat pumps who may not expect (or budget for) the concentration of costs in the coldest weeks. The variation in cost per kWh using a heat pump during colder periods will be more significant for consumers switching from natural gas due to the relatively low cost per kWh, however even considering the drop in CoP the running cost will still be lower than other forms of electric heating. This challenge can be mitigated by information provision to support households plan for seasonal variations in heating costs, and/or alternative payment options to spread costs through the year.

A3.4 Installation costs

The installation cost includes capital costs of the heating device, ancillary equipment, heat distribution system and the cost of labour to install these. Installation costs per kW for small domestic ASHPs are higher than for larger domestic or commercial heat pumps as the installation process and costs are similar. The smaller the heat pump, the higher the installation costs become as a percentage of the total capital costs[85].

Analysis of 15 domestic and non-domestic installations in London found that ASHP costs ranged between £900 and £2,900 per kW of installed capacity (not including heat emitters). For reference, domestic-scale heat pumps typically range between 3kW-20kW. The analysis indicated that GSHP and WSHP costs are typically more expensive per kW than ASHP costs, ranging between approximately £1,400 and £6,000 per kW of installed capacity[86]. The primary reason for the increased cost per kW is the additional cost for ground or water source collectors. Surface collector GSHPs require groundworks over a significant area, with hundreds of meters of collector pipes and manifolds on top of trenching and labour costs. Alternatively, a GSHP can use boreholes, with drilling costs for a small heat pump in the region of £6,500. WSHPs are more common in non-domestic settings as the collector requires either a large body of water to lay the pipes on the bed, or a filtration system and pumps that would make it uneconomical to consider in a domestic setting.

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[85] Delta-EE (2018) The Cost of Installing Heating Measures in Domestic Properties. A Report for the Department for Business, Energy and Industrial Strategy

[86] Carbon Trust (2020) Heat pump retrofit in London

Upgrading to larger radiators improves the efficiency of heat pumps by allowing for lower flow temperatures. The Carbon Trust's project in London found that where upgraded radiators were specified, an additional up-front cost of £3,517 was required. Average total capital costs, including radiators and hot water cylinder, were £11,747 for air source and £20,761 for GSHP systems[87].

Hybrid heat pumps

Research by BEIS[88] considered the costs of three options for retrofitting air source hybrid heat pump systems in properties on the natural gas grid. The options were:

- replacing an existing boiler with an integrated product (total installed cost £6,800-£9,300)
- adding a heat pump to an existing boiler (total installed cost £4,000-£10,000)
- replacing an existing boiler with a heat pump, a boiler and a controller package (total installed cost £6,300-£11,300).

The research indicated that the fully installed price of a hybrid system ranging from £4,000 to £11,300 is consistent with the price for standard heat pumps, for air source products.

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[87] Ibid

[88] BEIS (2016) Evidence Gathering - Low Carbon Heating Technologies: Domestic Hybrid Heat Pumps