

Diffusion, User Experiences and Performance of UK Domestic Heat Pumps

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Abstract

Heat pumps for space and water heating are recognised by EU governments as a key technology to meet carbon reduction and renewable energy targets, especially as electricity supplies are decarbonised. As a result of many socio-economic and technical factors, heat pumps are well-established in some EU countries, while in others including the UK, the market is immature. A field trial of heat pumps, found that, especially before specialist intervention, UK domestic heat pumps performed considerably less efficiently than those in Germany and Switzerland. This paper reports on the experiences and satisfaction of users in the field trial and the influence of technical and user factors on system efficiency. A comparative site analysis indicates that many interacting factors affect heat pump efficiency, including dwelling energy efficiency; heat pump system design and installation quality; and some of the characteristics and different heating behaviours of private householders and social housing tenants. The implications for low carbon energy policies, heat pump design and diffusion are discussed.

Key words: Renewable heat; Domestic heat pumps; Consumers and users

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INTRODUCTION

Nearly half (48%) of final energy use in the 27 countries of the EU is in the form of heat and this accounts for 86% of EU domestic energy use (European Commission, 2011). In the UK, heating accounts for 47% of carbon emissions and for the largest proportion of final energy demand at approximately 49%, of which about two fifths is domestic demand (DECC, 2012, 2013a). Heat pumps are one of the potentially most important energy saving, low carbon technologies for providing space and water heating in buildings. This paper examines recent research on the experience of adoption and use of heat pump systems in UK dwellings and the influence of technical and user factors on system efficiency. It also considers the implications for UK policies aimed at supporting the diffusion of heat pump technology to achieve carbon reduction.

1. HEAT PUMPS AS A LOW CARBON TECHNOLOGY

A heat pump is a device, usually electrically powered, for boosting low temperature heat in the ground, the air or water to temperatures suitable for heating a building and/or domestic hot water. Low temperature heat is absorbed from the ground, air or water via a fluid which first enters the heat pump's evaporator, turning the liquid into vapour. This vapour then passes into the compressor, where it is pressurised, and thus increases its temperature. The vapour then passes into the condenser where the vapour condenses to a liquid and releases heat into the building via emitters such as radiators or under-floor heating. This liquid finally passes through an expansion valve transforming it into a low pressure, low temperature liquid, and the cycle starts again. The two main types of system are ground source heat pumps (GSHPs) which extract heat stored in the ground via pipes buried in

trenches or in a deep borehole and air source heat pumps (ASHPs) which take heat from the air. GSHPs are usually considered to be more efficient than ASHPs due to the greater stability of ground temperatures.

The efficiency of a heat pump system is described by its coefficient of performance (CoP), which is the ratio of the heat output of the system to the electrical input to the heat pump's compressor at a given time. A more useful measure is the Seasonal Performance Factor (SPF), which is the heat pump system's efficiency over a year. Thus for a heat pump system with a SPF of three, for every kWh of delivered electricity the system generates three kWh of heat. However, the overall efficiency of the heat pump system also depends on the generation efficiency of the electricity used by the heat pump and hence on the mix of fossil fuels, nuclear and renewables in the electricity supply system of the country in which the heat pump is located.

Heat pump efficiency is important for their classification as a low carbon technology. Heat pumps are considered to be a renewable energy technology under the EU Renewables Directive, if their SPF is greater than 2.5. However, heat pumps should become increasingly low carbon given national policies to decarbonise electricity supplies. For these reasons several EU governments, including the UK, see heat pumps as a key technology to reduce carbon emissions and to contribute towards meeting binding carbon reduction and renewable energy targets. These include the EU's 20:20:20 overall target of 20% of total energy from renewables and a 20% reduction in greenhouse gas (GHG) emissions by 2020; and the UK's targets of 15% energy from renewables and a 34% reduction in emissions by 2020, building to an 80% emission reduction by 2050. The UK's National Renewable Action Plan (2012) to meet its EU carbon reduction targets sees a significant role for heat pumps by 2020, but mainly installed in non-domestic buildings. Some environmentalists have also become heat pump advocates. For example, the Centre for Alternative Technology's scenario for a zero carbon Britain in 2030 envisages that over half (54%) of domestic and 40% of non-domestic heat demand is met by heat pumps, supplied by renewable electricity (CAT, 2010).

2. MARKET ADOPTION AND DIFFUSION

The EU ProHeatPump project (Müller, Eichberger, Rummen, Russell, Thonon, and Nordman, 2009) provided information on the market for heat pumps in Sweden, France, Germany, Bulgaria and the UK. The project found that heat pumps are well-established in countries where electricity is relatively cheap and electric heating of homes is common; for example in Sweden where there are no natural gas networks and electricity prices are relatively low due to the availability of hydroelectricity

and nuclear power. Thus GSHPs are installed in about 10% of Swedish homes, including 80% of rural ones.

In France, gas and oil are cheaper than electricity, despite the high proportion of nuclear electricity. Nevertheless heating costs in many French homes can be substantially reduced by installing an efficient heat pump. Hence in the two years 2009 to 2010, nearly 200,000 heat pumps were sold in France, mostly ASHPs, about half of which were retrofitted in old properties (Sugden, 2011).

In Germany electricity is expensive, at about twice the price of gas and oil, partly due to the generous financial support for renewable generation. However, with a heat pump cost and carbon savings can be made, especially given Germany's well-insulated buildings and 25% of electricity currently generated by renewables. For the 1.3 million household renewable energy generators in Germany (McGrath, 2013), installing a heat pump system is an excellent way of utilising their electricity. Thus by 2007 there were about 300,000 heat pumps in Germany with rapid market growth. For example, over 60,000 heat pumps were installed in 2009, with the result that about a quarter of German new buildings have heat pumps (Delta Energy, 2010; RWE, 2009). In Germany heat pumps will become an increasingly low carbon technology under the *Energiewende* ("energy turn"), the country's politically supervised shift from nuclear and fossil fuels to renewable sources of energy.

In the UK, the heat pump market and industry is still immature. A major government commissioned study estimated that by 2007 there were less than 2000 ground source heat pumps in the UK; although no data for air source heat pumps were provided (Element Energy, 2008). This is mainly because, following the discovery of relatively cheap North Sea natural gas in the 1960s, 80% of UK homes now have gas central heating (DECC 2012). Another major factor hampering the UK heat pump market is because electricity is comparatively expensive and carbon intensive, it is more difficult for domestic heat pumps to produce carbon savings when compared to mains gas central heating. However, heat pumps can be competitive with oil central heating and are cheaper to run and less carbon intensive than direct electric and solid fuel heating. Hence the main market for heat pumps in the UK so far has been among the five million rural properties that are off the main gas network and which use oil, electricity or solid fuel for heating and in social housing projects in which old heating systems were being replaced.

It is partly for these historical reasons that the UK Government argues in the Low Carbon Heat Strategy that heat pumps are the best form of low carbon heating for rural off-gas and selected suburban locations, while most urban and suburban properties are best served initially by efficient condensing gas boilers and in the future by low carbon district heating networks (DECC, 2012). There is some indication that the UK heat pump market is taking

off, to some extent stimulated by government financial incentives such as the Low Carbon Buildings Programme. In 2009 and 2010 approximately 8000 ground source and 30,000 air source heat pumps were installed, almost all in residential buildings, and focused on off-gas locations (Fritsch, 2011). The market is expected to expand further following the introduction of the Renewable Heat Incentive, available for public and commercial buildings in 2012 and for domestic dwellings in 2014 (EST, 2013a).

Overall, however, despite such signs of growth Fawcett (2011) says:

Within Europe a significant market for residential heat pumps exists only in Sweden, Switzerland and parts of Austria. In other countries the market share of heat pumps remains small, and the heat pump is not considered a first choice when installing or replacing heating and hot water equipment (p.1549).

Our previous research found that the demand for domestic low carbon and renewable energy technologies, including heat pumps, was largely confined to niche markets of middle-class, environmentally aware consumers plus a few progressive social housing providers (Caird and Roy, 2010). Most UK consumers and plumbers, and many architects and heating engineers, have no experience of heat pumps and so would not normally consider them in preference to dominant conventional heating systems. This and other research found that a number of barriers have to be overcome for heat pumps to be adopted widely beyond their established markets. These include the high upfront cost of heat pump systems and a long payback period; their greater complexity to design and install compared to conventional heating systems; and consumer factors including, lack of awareness and information, the technical knowledge involved in deciding to buy a heat pump and then operate it efficiently, and scepticism regarding the performance of unfamiliar technologies (Watson, Sauter, Bahaj, James, Myers, and Wing, 2006; Element Energy, 2008; Caird and Roy, 2010).

Heat pumps offer a different approach to domestic heating, normally producing heat at lower temperatures than conventional systems. As their efficiency is dependent upon a small temperature lift from heat source to heat emitter, they operate most effectively in well-insulated buildings with larger low temperature heat emitters, preferably under-floor heating. This makes them well suited to new-build projects where heat pump systems are easier to install. As the majority of homes have already been built most installations would need to be retrofitted. Because of the lack of space to install ground collectors, retrofits often involve an air source heat pump with potential fan noise problems for occupants and neighbours. In most cases retrofitting also involves the disruption of installing larger radiators or under-floor heating and requires sufficient space for equipment such as pumps and water tanks.

3. UK HEAT PUMP FIELD TRIAL

There are therefore a number of technical, social, economic and consumer barriers to the diffusion of heat pump technology. However, even if these barriers can be overcome, for example with the help of the various financial incentives and promotional campaigns that exist in Europe, such as those discussed in Müller et al (2009), the competitiveness of heat pumps in terms of running cost and carbon emissions depends on their actual efficiency. Manufacturers and installers typically claim CoPs/SPFs of between 3 and 4. But such figures are obtained under laboratory conditions and it is not known if these efficiencies can be obtained in actual household use.

For this reason the UK's main energy advice body, the Energy Saving Trust (EST), established a national heat pump field trial, which aimed to find out how a large sample of heat pump systems performed in real UK domestic installations. This information would help consumers, social landlords and installers to decide whether a heat pump would be worth installing and help the government decide whether heat pumps should be widely promoted in Britain as an alternative to conventional heating and hot water systems.

After a year of monitoring from 2009-10 of a randomly selected sample of 83 heat pump systems located at sites across the UK, the EST's field trial found that the systems generally had much lower efficiencies than claimed by their manufacturers. In the trial heat pump performance was measured by its system efficiency (SEFF). (SEFF is a measure of average efficiency over a year similar to SPF, but for systems that provide domestic hot water SEFF only includes the heat delivered to hot water taps, while SPF includes the heat supplied to the hot water tank before tank losses, and hence gives a slightly higher efficiency figure.) There were also some complicating factors in the trial, such as difficulties controlling for different qualities of heat pump system design and installation, as all had been commissioned before the introduction of the Microgeneration Certification Scheme (MCS) quality standard for UK heat pumps (DECC, 2013b).

Table 1
Average Monitored Annual Efficiencies of Heat Pump Systems

	GSHP	ASHP
UK systems (SEFF)*	2.39	1.82
German and Swiss systems (SPF)	3.5	2.7

* Before subsequent intervention to improve underperforming systems

The system efficiencies found in the trial varied widely: from 1.3 to 3.3 (mid range 2.4) for the GSHPs and from 1.2 to 3.2 (mid range 2.2) for the ASHPs. That

means for every kWh of electricity used on average the GSHPs produced 2.4 kWh of heat and the ASHPs 2.2 kWh of heat (EST, 2010). Re-analysis of the data by the Department of Climate Change to take into account some additional information produced mean efficiencies of 2.39 for the GSHPs and 1.82 for the ASHPs (Dunbabin and Wickins, 2012).

These measured efficiencies of UK heat pump installations are considerably worse than the performance of German and Swiss heat pump systems whose monitored efficiencies are typically about 3.5 for GSHPs and 2.7 for ASHPs (Fraunhofer ISE 2011; Delta Energy 2011)—Table 1. Although these results are not directly comparable due to the slightly different measures of annual efficiency noted above, they indicate that while a few UK systems performed as well as German or Swiss ones, most of would not count as renewables under the EU Renewable Energy Directive, which require minimum SPF efficiency of 2.5.

4. THE HEAT PUMP USER STUDY

As well as measuring efficiencies, the EST heat pump field trial also attempted to find out *why* so many UK heat pump systems were not performing as well as claimed by their manufacturers or as well as German and Swiss systems. This investigation examined technical factors, such as the type of heat pump, the design of the system, details of installation, etc., and also considered user and building efficiency factors. User factors are important because it is known from other household energy monitoring studies, for example, of microCHP systems (Carbon Trust, 2007) and solar water heating systems (EST, 2011) that consumer behaviours and preferences, such as how users operate their system, can have a major effect on its performance.

A team from the UK Open University were engaged as partners in the field trial to conduct the user research by obtaining feedback from users on their experience of owning or using a heat pump system and also to identify and analyse the effects that users' characteristics and behaviours might have had on the performance of their system. The field trial included both private householders who had bought a heat pump and social housing tenants who had one provided for them. The private installations were generally in new-build, converted or extended large detached houses occupied by couples or families, while the social housing installations were mostly retrofits in small flats or bungalows typically occupied by one or two people, who were often elderly or disabled (Table 2).

Table 2
User Sample by Heat Pump System, Housing Tenure, Property and Occupancy Characteristics

	Private householders	Social residents
Heat pump system type		
GSHP	60% (29)	67% (20)
ASHP	38% (18)	33% (10)
Water source heat pump	2% (1)	0
Base	48	30
Type of property		
Detached house & Bungalow	81% (33)	3% (1)
Semi-Detached	12% (5)	63% (19)
Terraced	5% (2)	27% (8)
Flat	2% (1)	7% (2)
Base	41	30
Number of bedrooms		
1-2 bedrooms	23% (10)	79% (23)
3-6 bedrooms	77% (34)	21% (6)
Base	44	29
Size (floor area)		
Average floor area size (m ²)	175	64
Base	48	30
Energy Performance Certificate (EPC) bands (measured RdSAP)		
0-54 (Band E,F,G)	41% (18)	30% (9)
55-68 (Band D)	27% (12)	63% (19)
69+ (Band C,B,A)	32% (14)	7% (2)
Base	44	30
New-build versus retrofit system		
Newbuild/Converted Property	59% (19)	7% (2)
Major Extension	16% (5)	0%
Retrofit system in existing property with no extension	25% (8)	93% (28)
Base (note smaller sample)	32	30
Household occupancy		
1 person	4% (2)	70% (21)
2-7 people	96% (43)	30% (9)
Base	45	30

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4.1 Methods

An initial questionnaire was mailed to the private householders whose systems had been randomly selected for the field trial from the EST's database of heat pump installations to invite participation in the user study—very few refused. Householders who agreed to participate

were then mailed in-depth postal questionnaires covering autumn, winter and spring/summer seasons. In the case of the social housing sites, permission was obtained from the five social housing managers participating in the trial to contact their residents. All the social housing residents were then mailed a questionnaire covering all seasons. Interviews with managers provided additional information about their residents, the properties and heat pump systems. 48 out of 55 private householders and 30 out of 34 social housing residents returned questionnaires, an overall 87.6% response rate. An MS Access database was specially developed to store and analyse the large amount of user data collected and relate this data to the site survey information and heat pump system performance measurements from the field trial.

4.2 User Experiences of Their Heat Pump System

Detailed findings of the user surveys have been provided in other reports and papers (EST, 2010; Caird, Roy and Potter, 2012). In summary, the surveys showed that most users were very satisfied with their heat pump systems. Nearly three-quarters (74%) of users agreed that the system met their household's room heating requirements. Even more (83%) agreed that the system has made their home warm and comfortable. For example, one GSHP user in a private dwelling admitted, "it took a bit of getting used to it because under-floor heating does not provide a direct heat source. We now think it gives a much more comfortable, even temperature".

Most 80% said they got pleasure and satisfaction from using what they perceived as a low carbon heating system. And three quarters (75%) said the heat pump was much better or better than their previous heating and domestic hot water system, although in almost 90% of cases the heat pump was replacing direct electric, oil wood or solid fuel heating in homes without main gas central heating.

Several open-ended comments indicated that the constant warmth provided by a heat pump was one of its main advantages over their previous system and that in some cases changing to a heat pump system involved "comfort-taking"; for example heating rooms for longer and/or to higher temperatures than before. Although any comfort-taking may simply be the result of the recommended method of operating a heat pump continuously, it would have the effect of reducing some of the cost and carbon benefits of switching to a heat pump system.

Nearly three quarters (74%) of the users had systems that supplied domestic hot water as well as space heating. For these systems, satisfaction with hot water provision was high. Most (86%) of these users agreed that the system met their household's hot water requirements, with only 10% disagreeing.

Despite these generally high levels of satisfaction, a sizeable minority of users expressed dissatisfaction and/or

experienced various problems in use. The main complaints from users were nearly a half (44%) not knowing how to operate their control system for optimum efficiency and economy and nearly a third (31%) having difficulties understanding operating instructions. Also, over a fifth of users reported problems with heating their home to desired temperatures (24%); and/or the slow warm up of their heating (21%); and/or heat pump noise, especially from ASHP fans (21%).

Perhaps not surprisingly, the private householders, most of who had chosen to invest in a heat pump and who owned most of the higher efficiency systems measured in the field trial, generally expressed higher levels of satisfaction and had fewer problems with their systems than the social housing tenants, who had a system provided, or in a few cases imposed on them. For example, 91% of private householders were satisfied with the warmth and comfort provided by their system compared to less than three quarters (71%) of social housing residents. 27% of social housing tenants said their heat pump was worse than their previous heating system compared to 7% of private owners. A third of tenants (33%) said they had problems with heat pump fan noise compared to less than 10% of private householders, probably because the heat pump was sited closer to living and bedrooms in the social housing than in the larger private homes.

Most heat pump users want a system that provides all of their heating needs. A majority (61%) of the systems designed to provide 100% heating were said by users to have provided all of the household's room heating requirements in the cold winters of 2008-9 or 2009-10. But nearly a third of heat pump users (31%) said they used secondary sources of heating in winter, on at least some occasions. Typically the secondary heating was wood stoves by the private householders and electric room heaters by the social housing residents. The use of secondary heating, however, does not necessarily mean users were dissatisfied with their heat pump. About half of users who employed secondary heating did so from choice, for example for the pleasure of heating a living room with a wood stove; otherwise secondary heating was required to meet a short-fall in heat pump output, usually in the coldest weather.

Given the complexity of heat pumps compared to conventional heating systems, good technical support and advice for users is especially important. Advice and support on using heat pumps is usually available from manufacturers, installers and, for social housing residents from housing managers. While nearly two-thirds (63%) of users were satisfied with the technical support they received, nearly a quarter (22%) were dissatisfied. Most of the dissatisfied users were social housing residents who would have liked to have received more advice on how to operate and control their system to meet their requirements for economical and comfortable heating.

5. WHY DO SOME UK HEAT PUMP SYSTEMS UNDER PERFORM?

A statistical analysis of the monitoring data was conducted by the EST in an attempt to discover which technical factors affected heat pump performance. This was unable to provide an explanation for the wide variation in the efficiencies of the heat pump systems in the field trial or for the poorer performance of the systems in the UK compared to those in Germany and Switzerland. The only technical factor that emerged was that heat pumps seem to be more efficient when operating near maximum output. However, a subsequent more detailed analysis of under-performing sites by Dunbabin and Wickins (2012) indicated a number of technical design and installation factors that contributed to poor performance including:

- Undersizing of the heat pump—this meant that direct electric top-up heaters switched on when heat loads were high, contributing to a significant reduction in overall system efficiency and high running costs;
- Undersizing of the ground collector (GSHPs)—this meant that insufficient heat was extracted from the heat source;
- Poor insulation of pipework and/or hot water cylinders, resulting in heat losses;
- Radiator or under-floor heating flow temperatures set too high by the installer—this meant that the heat pump had to boost the source temperature more than necessary, which has the effect of reducing efficiency;
- Over-sizing of the heat pump—this could result in the system short cycling and operating inefficiently at low output, a particular issue for smaller dwellings.

Boait, Fan and Stafford (2011) had previously found that for well-insulated small dwellings, such as some of the social housing in the trial, the smallest available GSHP at 5kW was too powerful and hence would not operate at design efficiency. These researchers also reported similar difficulties with the control systems among social housing residents as we found in our user research.

However, these investigations did not consider user-related factors in any detail. This therefore warranted further examination, as the data showed striking differences in user characteristics, heating behaviours and satisfaction levels of the user groups who had systems with higher efficiency compared with those with lower efficiency. The OU team therefore examined whether user characteristics and behaviour were related to heat pump system efficiency (SEFF). The user factors were then classified against the system efficiency data obtained from the technical monitoring, which was categorised into low (SEFF<2.0), medium (2.0-2.5); and higher system efficiency (>2.5) sites (Table 3).

Table 3
Characteristics of Heat Pump Trial Sites Categorised by System Efficiency (SEFF)*

Characteristic	SEFF <2	SEFF 2-2.5	SEFF >2.5	Total
Private housing	54% (12)	42% (11)	95% (21)	44
Social housing	46% (10)	58% (15)	5% (1)	26
GSHP	45% (10)	77% (20)	73% (16)	46
ASHP	55% (12)	23% (6)	27% (6)	24
Base	22	26	22	70

* measured by system efficiency (SEFF). Pump COP is used for a few cases where SEFF was not available. Data is based on final analysed monitoring results as updated in April 2011.

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Chi-squared non-parametric tests were then used to calculate the statistical significance of the observed versus expected relationships and hence to test the hypotheses. The results suggested that greater user knowledge and understanding of the heat pump was significantly related to higher system efficiency ($p = 0.018$). 82% of users of higher performing systems claimed to have either a lot or a fair knowledge of their heat pump system. This contrasted with only one user of a low performing system who described themselves as having a lot of knowledge of their system. Not surprisingly there was a big difference between heat pump users in private and social housing with over 80% of private owners saying they had a lot or a fair knowledge of the system, given they had been engaged throughout the purchasing and installation process, compared to 40% of social tenants.

Our results also suggested that more continuous operation of the system under automatic control was significantly related to higher system efficiency ($p = 0.02$). Manufacturers and installers usually recommend leaving heat pump systems continuously on during the heating season because they work most efficiently when the system gently maintains room temperatures rather than having to regularly heat up a house from cold. All the higher performing systems were left on at night and 95% were left on when the property was unoccupied. This contrasted with 59% of low efficiency systems that were left on at night and 56% when the property was unoccupied. Significantly fewer social housing residents (55%) than private householders (84%) reported that their system normally operates continuously under automatic control. This is partly because some social tenants were not convinced that running a heating system 24/7 is an economical way of heating and so timed or switched their system on and off. As one social housing manager commented, when interviewed: “Some people have had previous systems where they have learned rules such

as switch it off if you're out...this is not the most cost-effective route for a ground source heat pump.”

As well as the above, hypotheses relating other user factors to system efficiency were also tested. These included differences in room temperature settings, in ventilation behaviour, in use of secondary heating, in the ease of using controls and satisfaction with technical support. However, none of these on their own were statistically significant. A larger sample would be needed to confirm the chi-squared test findings, which should therefore be regarded as indicative.

Examination of the relationship between housing type and heat pump efficiency showed that the system efficiencies of the heat pumps installed in the private homes were very significantly higher than in social housing ($p = 0.0001$). Almost all of the higher performing systems were found in private housing and only one in social housing. The reason for this strong association between housing type and system efficiencies depends on the interaction of several variables. These include the larger average size and higher average energy efficiency of the private dwellings; the greater proportion of new-build systems with under-floor heating in the private housing, while the social housing had a greater proportion of retrofit systems with conventional radiators. Other differences already mentioned are the greater knowledge and understanding of the private householders, the non-continuous heating patterns more frequently adopted by the social housing residents and the possibility of oversized heat pumps in the small social housing properties.

6. COMPARATIVE SITE ANALYSIS

The approaches to analysing the data collected as part of the heat pump field trial focused on statistical reporting and testing of specific factors. Because heat pump performance seems to depend on many interacting technical, user, dwelling and site factors, the authors developed a new analytical framework to examine the reasons for the differences in the annual performance of the best and worst performing UK systems. A sub-sample of the highest and lowest efficiency systems in the field trial with the most detailed data available were selected for comparative analysis, to include 10 high efficiency (SEFF >2.5) and 17 low efficiency (SEFF <2) systems for comparison on a number of factors against criteria for better heat pump efficiency. (More low efficiency systems, with system efficiencies below 2.0, were included in the analysis than high efficiency ones because there were only relatively few heat pumps with a system efficiency above 3.0).

The comparative factors used data gathered on the following variables:

- (a) the energy efficiency, size, age of the dwelling and

whether the heat pump was part of a new-build or retrofit project (obtained from the EST's site surveys);

- (b) the heat pump type (ground or air source), the heat source and type of heat emitter (radiators and/or under-floor) and whether the system provided domestic hot water (obtained from the EST);

- (c) user characteristics from the OU surveys; including whether private householder or social tenant, their level of knowledge and understanding of heat pumps, how easy they found using its controls, difficulties with understanding instructions or how to operate the system;

- (d) user behaviours from the OU surveys, including whether heating was continuous or not, room and hot water temperature levels and ventilation behaviour (e.g. whether users opened windows with the heating on).

Hypotheses were established on how a particular factor might be related to heat pump efficiency and a weighted score (mainly on an ordinal scale) was given according to the likely direction and strength of the relationship; where a higher score was associated with higher efficiency. For example, heat pump systems installed in newer, larger, well-insulated buildings with larger heat emitters (e.g. under-floor heating) and used more continuously to provide space heating by users with high levels of knowledge and understanding were expected to have high system efficiency.

The findings from this analysis showed, as expected, that the highest efficiency systems met more of the expected conditions for optimal domestic heat pump performance, achieving higher total scores than the lowest efficiency systems. The statistical difference between the distribution of scores for the high and low performing heat pump samples were tested using the Mann-Whitney directional U test and found to be significant ($p = 0.002$). Though this tests non-parametric data gathered as a result of qualitative assessments and therefore has limitations, the findings indicate that the difference between the performance of high and low efficiency systems may be explained by a cluster of interacting user and dwelling factors as well as the technology, design and installation of the heat pump system.

This analysis found that higher efficiency systems were associated with more energy efficient dwellings with larger floor areas, often with major extensions and new builds, although not one of these characteristics was common to all. For example, only two of the high performing systems were installed in properties with RdSAP ratings below the average UK dwelling RdSAP rating of 41 points. The householders at these sites were either dissatisfied with their system's running costs and fuel bills or unsure, perhaps because, despite the efficient heat pump, the low dwelling efficiency resulted in fabric heat losses and high fuel bills.

On this analysis higher system efficiency did not depend on whether the heat pump source was ground

or air source, or whether domestic hot water was provided, or whether the heat was distributed to under-floor heating or radiators. A higher proportion of users of higher efficiency systems tended to have greater knowledge and understanding and exhibited heating preferences and behaviours, such as for more continuous heating to lower temperatures, but again there were exceptions. By comparison a high proportion of the low efficiency systems were identified by the EST as having technical faults, and although faulty installation was not characteristic of all low efficiency systems, it makes comparative analysis of other factors difficult, as it is not known what the results would have been if the sample had only included fault-free installations. So whilst no one factor can be identified as essential for optimal heat pump performance, this analysis shows that there are interacting factors that are likely to include user variables and dwelling characteristics as well as technical factors.

Although reference was sometimes made to the need to improve user understanding and provide more user-friendly controls, the publicity and debate following the release of the EST heat pump field trial findings in 2010 focussed mainly on improving the quality of system design and installation. Government and industry bodies therefore mainly responded with the issue of more detailed MCS standards for accredited installers (DECC, 2013b). Subsequently, the Energy Saving Trust decided to carry out a detailed follow-up study to discover why many of the field trial systems were underperforming and if their performance could be improved.

The follow-up study, completed in 2013, monitored 44 systems, 38 of which were from the original trial. In the study manufacturers and installers investigated and carried out modifications to 32 poorly sized or underperforming heat pumps, where possible to meet the new MCS standards. In addition users were provided with guidance to improve understanding of the controls and how best to manage heat pumps to optimise performance. At the end of the study users' satisfaction with their system was surveyed. This resulted in improved average SPF efficiencies of 2.82 for the ground source and 2.45 for the air source heat pump systems and higher levels of user satisfaction. The EST concluded that with the improved quality standards and given better user understanding, heat pumps can perform very efficiently in UK homes, with 80% of the systems in the phase two trial counting as a renewable energy technology under the EU Renewables Directive (EST, 2013b).

CONCLUSIONS

The take-up of heat pumps for providing heating and domestic hot water differs considerably in different European countries as a result of the interaction of many environmental, economic, technical, social, political, regulatory and market factors. The reasons include the

different environmental conditions, energy policies and fuel prices in the different countries; for example the availability of relatively cheap hydro and nuclear electricity in Sweden, while in Britain gas became the dominant domestic heating fuel following the discovery of North Sea natural gas in the 1960s.

Market diffusion also reflects the development of the heat pump manufacturing and installation industry—for example mature in Sweden and immature in the UK. The level of maturity of the heat pump industry arises at least partly from the market opportunities for selling this technology, itself dependent on relative fuel prices, the dominance of conventional heating systems, and awareness of the technology among specifiers, installers and consumers.

Heat pumps extract and deliver low temperature heat and so are best suited to heating energy efficient buildings. So different building regulations and quality standards may be another reason for the relatively higher market penetration of heat pumps in certain countries; for example a tradition of highly insulated and air tight buildings in Sweden, necessitated by the harsh winter climate, compared to the low levels of insulation and air tightness of most existing UK housing.

Heat pumps are also expensive and, in the UK and many other EU countries, a heat pump system costs two to three times that of a gas central heating system (Müller et al., 2009) and is not likely to be cheaper to run. UK Government incentives for consumers to install heat pumps such as the Low Carbon Buildings Programme have had a relatively small effect on sales, although the 2013 Renewable Heat Incentive which will pay householders for each kWh of heat generated by a heat pump, if sufficiently generous, could result in significant market growth if this follows the pattern of the feed-in tariff for solar PV systems. Nevertheless, it is clear that the take-up of heat pumps is not just a matter of economics, but depends on a multiplicity of issues, among them how efficient heat pumps are in real installations. System efficiencies, coupled with the carbon intensity of the electricity supply system, in turn determine the level of carbon emissions from heat pumps relative to other heating and hot water systems; and indeed whether heat pumps can be classified as a renewable heating technology.

The paper has shown that the efficiency of heat pumps, and the reasons for the apparent underperformance of UK heat pumps compared to Swedish and German systems, is also a matter of many interacting factors. These include the design and sizing of the system for the particular household and property plus the quality of its installation. This is supported by the research by Boait, Fan and Stafford (2011), which concluded that the sizing of heat pump systems needs to be better matched to the size and thermal characteristics of UK dwellings.

Designing and installing a heat pump system is

considerably more complex than a conventional heating system and requires experienced and trained professionals. The relative immaturity and fragmentation of the UK heat pump industry seems to have resulted in a proportion of under-sized or over-sized, inadequately designed and poorly installed systems. This was not helped by fact that the OU user surveys found that some private householders had to act as project managers for installing their heat pump system, co-ordinating multiple contractors and taking responsibility for the quality of the installation. The UK government certification of installers and improved training, which came into effect after the installation of most of the field trial systems, was shown in the EST (2013b) follow-up study to improve performance.

The interacting effects of dwelling size, age and energy efficiency; user knowledge and understanding of heat pumps and their controls; and user heating and ventilation preferences and behaviour were indicated by the significant differences in heat pump efficiencies in the private and social housing in the field trial. It is not certain how important these effects are, but it is clear from the OU surveys that many users find heat pump systems and in particular their complex controls difficult to understand and operate economically. Installers and social housing managers need to do more to set up systems correctly, explain their operation and controls to users, and provide good after-sales support. Heat pump manufacturers could also play a part in improving the acceptability of heat pump systems by (a) designing more user-friendly instructions and control systems—some manufacturers have already improved the user interface of their controls since the field trial installations; (b) developing controls and displays that provide users with feedback on system operating efficiency, money and carbon savings; (c) displays that indicate when a direct electric auxiliary boost heater in the system has switched on, to allow users to decide whether to use secondary heating in cold weather. The OU surveys found that some users unexpectedly had very high electricity bills because there was no indication that the system was operating on auxiliary direct heating. The EST (2013b) follow-up study confirmed that users not realising when their system was running on the electric boost heater was an important control issue that needs to be addressed.

The EST field trials have shown that well-designed and installed heat pumps are attractive to consumers and can operate efficiently in UK conditions. Most systems in the field trial were installed at sites without mains gas. This means that, even given the relatively low average efficiencies of the systems, most should reduce carbon emissions as replacements for oil, solid fuel or electric heating. However, even after the interventions in the follow-up study, some of the systems would not save carbon as a replacement for gas central heating or count as a renewable energy source under EU rules, given the existing UK grid electricity fuel mix. The

UK government strategy for domestic low carbon heat therefore focuses mainly on off-gas rural properties for heat pumps and is relying on the future decarbonisation of the electricity system to enable heat pumps to penetrate more widely into suburban and urban areas. The rate and degree of decarbonisation is a matter of contested energy policy and considerable uncertainty, so understanding why and how the performance of UK heat pump systems can be improved to German and Swiss levels is an essential first step.

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