# ADOPTION OF AIR SOURCE HEAT PUMPS FOR LOW CARBON HOMES

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Air source heat pumps (ASHP) are a recognized form of low carbon technology, and have been encouraged in the UK for supplying space and water heating in the domestic sector. However, the UK uptake is low compared to many other countries, with previous research having reported real and perceived barriers in both cost and non-cost terms. This paper contributes to the knowledge by examining the operational efficiency of ASHP and exploring the perspectives of the developer and householders on utilizing such systems. The research was carried out through a case study with a medium-sized developer utilizing ASHP for a low carbon new-build development in East England. The case study involved document analysis, face-to-face interviews with the firm's senior management team, and a postal questionnaire survey of occupants in homes installed with an ASHP. The performance of ASHP systems in typical occupied homes was compared with that in a monitored 'prototype' property. The results reveal that the ASHP efficiencies measured in these two ways were generally consistent. The householders were positive of the economy, space impact, reliability and maintenance of ASHP, but negative of its visual impact and the noise issues. Furthermore, the majority of respondents were willing to choose or recommend a property installed with an ASHP. However, occupants' lack of understanding of efficient ASHP operation was identified as a significant barrier to realizing the full benefits of using such technology. Although the developer utilized ASHP for building low carbon homes, they were concerned about the not yet well-established supply market and the current lack of ASHP efficiency recognition in the regulatory framework. The findings should enable more informed decisions of adopting renewable technology in low carbon home building.

Keywords: air source heat pump, efficiency, low carbon, new-build homes, renewable technology.

## INTRODUCTION

With fossil fuels rapidly depleting, renewable energy sources are becoming increasingly important to addressing the energy supply crisis and global warming (NHBC Foundation 2009). Housing contributes 27% to the national annual carbon dioxide emissions in the UK, of which 53% is due to space heating and 20% for water heating (Department of Communities and Local Government 2007). With such context UK Building Regulations Part L: conservation of Fuel and Power has progressively evolved in order to achieve the government's objective of zero carbon homes by 2016. A reduction in the target annual carbon dioxide emissions rate (TER) was made in 2006, by between 20% and 27% from a notional building based on Part L 2002, and a further reduction by 25% on the basis of Part L 2006 followed, to be in

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effect from late in 2010 (Department of Communities and Local Government 2009a; Hamza and Greenwood 2009).

Air source heat pumps (ASHP) are recognized as a form of renewable energy technology, and have been encouraged in the UK for supplying space and water heating in the domestic sector. However, despite the benefits of using ASHP (see e.g. Cockroft and Kelly 2006) the UK uptake of such technology is low comparing to many other countries (Rawlinson 2008). Previous research (e.g. Pan and Cooper 2010) suggests that a combination of real and perceived barriers exist, in both cost and non-cost terms, to the diffusion of ASHP technology in the UK domestic sector. However, the study of heat pump operational efficiency in occupied homes and how the householders perceive the benefits, if any, of using such systems is limited. Therefore, this paper aims to address this gap in knowledge by examining the operational efficiency of ASHPs installed in occupied new-build dwellings, in comparison with the system monitored in a 'prototype' property. The paper, drawing on the literature review, scrutinizes the factors influencing the operational efficiency of ASHPs within the general context of the driving forces and inhibiting factors for the uptake of such technology. Through the adoption of the developed methodology it also critiques the energy consumption data and analysis carried out of a low carbon new-build development, and discusses the implications of the empirical data collected through this study on both research into and practice of low carbon home building.

## LITERATURE REVIEW

### Drivers for and barriers to adopting ASHP technology

Various drivers and barriers co-exist in UK housing, which influence the decisions of developers and house owners to adopt or disregard ASHP technology. For larger housebuilders, the benefits of enhanced brand recognition and reputation for attracting customers are powerful drivers due to sustainability publicity and implementing a sustainability policy as part of Corporate Social Responsibility (Osmani and O'Reilly 2009). This approach also benefits residents by broadening their awareness of who can help them integrate renewable technology into their homes (BERR 2008). Various forms of financial incentive are available such as the Low Carbon Buildings Programme (Department of Energy and Climate Change 2009) and the Renewable Heat Incentive scheme which is currently in consultation with a proposed introduction in April 2011 (Department of Energy and Climate Change 2010). Also, residents can benefit from a fixed tariff subsidy by adopting renewable heat systems accredited in the Microgeneration Certification Scheme product list (for which ASHP is qualified) (ibid.). These incentives, together with the evolving regulations and a growing culture for more sustainable lifestyles, encourage the adoption of ASHP in UK housing.

Considerable barriers to adopting ASHP have also been reported, which include: a lack of qualified personnel, noise, vibration and visual impact (Fisher *et al.* 2008), a lack of awareness and knowledge, reluctance of end-users, resource constraints, and unfavourable planning permission requirement (BERR 2008). In particular, developers perceive renewable technologies as unreliable and integrated at the detriment of profit, space and aesthetics (Osmani and O'Reilly 2009). Residents are alternatively concerned over the noise pollution (Davis and Harvey 2008), and also are reluctant to deviate from the use of traditional heating systems. Consequently, there is a lack of awareness of renewable technologies and their benefits (Department for Business, Enterprise and Regulatory Reform 2008), which results in clients' lack of sustainability requirements for development (Osmani and O'Reilly 2009).

Furthermore, a perceived or real elevated cost of achieving superior environmental standards, e.g. the Code for Sustainable Homes (CfSH), has generated reluctance of developers to initiate innovation (ibid.). Such reluctance is also shared by home owners as revealed by Davis and Harvey (2008) which reported that only 6% of respondents would pay as significant as £35,000 in order to achieve zero carbon.

**ASHP efficiency debate**

The ASHP supply and manufacture industry often claims an achievable efficiency of 350% or higher (see Pan and Cooper 2009). However, these efficiencies are reduced in SAP 2005 (Standard Assessment Procedure) which stipulates maximum heat pump efficiency of 250% for design purposes. This is subject to a further reduction by 25% for utilizing higher temperature radiators, irrespective of tested performance (BRE 2009). Consequently, such stipulations have an adverse impact on the energy and carbon emissions calculations of new-build homes. However, neither method of calculation seems to be absolutely correct, as both inevitably have inherent biases. This conflict may be relieved through the introduction of SAP 2009 (Department of Communities and Local Government 2009b) by switching from seasonal energy calculations to monthly, which will enable the effect of monthly weather variations to be considered and therefore improve accuracy. Such amendments will also allow manufacturers to add the specific COP of their heat pump system to the SAP database. Further, SAP 2009 proposes a new methodology for calculating carbon emissions factors, by which the factor for electricity will increase by 40% from 0.422 to 0.591 kg $CO_2$/kWh. In comparison, the factor for mains gas will increase by only 6% from 0.194 to 0.206 kg $CO_2$/kWh. This change may have a significant impact on recognizing the efficiency of electric heat pumps, i.e. any potential efficiency ‘gains’ as a result of the increased COP may be offset or compromised by the effects of the carbon dioxide emissions factors changes (Hughes 2009). In addition to the regulatory influences, the efficiency of ASHPs may also be affected by non-technical factors during the operation of the system, which is often overlooked.

**Factors influencing ASHP operational efficiency**

A range of factors may influence energy consumption and ASHP operational efficiency, and they are grouped around three areas: building, design and occupancy (summarized on Table 1). In terms of building characteristics, NHBC Foundation (2009) suggested that the amount of energy consumption is highly dependent on the size and type of the building. This claim is supported by Santin *et al.* (2009) and Yohanis *et al.* (2008) who found a linear correlation between household size and energy use. This statement is however in disagreement with Wright’s (2008) observation of a ‘very weak’ correlation between energy usage and ‘built form’. Clearly, such discrepancies are attributed to influence of other factors.

Regarding design, the dwelling location and heating system specification and controls are influential on the total energy consumption (Yohanis *et al.* 2008). Tommerup *et al.* (2007) identified that energy consumption increases by about 10% per degree of internal temperature. In addition, Santin *et al.* (2009) found a linear relationship between the energy demand for space heating and the internal temperature and temperature setting. Santin *et al.* explained that properties with a thermostat have higher energy use due to the occupants being more aware of the internal temperature. Consequently, higher temperature settings increase the ASHP temperature lift, and therefore reduce COP whilst increasing power consumption (Grigg and McCall 1988). This is a prime example of the influence that occupant behaviour and characteristics have on energy consumption, which is often neglected in energy analyses.

*Table 1: Factors influencing ASHP operational efficiency and energy demand*

| Category | Factors improving efficiency or reducing energy demand | Factors reducing efficiency or increasing energy demand |
|---|---|---|
| Technology related | Increase in source air temperature (Grigg and McCall 1988);<br>Low heating distribution temperature, reduces temperature lift (Fisher *et al.* 2008; Brown 2007);<br>Increase in water flow rate lowers temperature lift (Grigg and McCall 1988);<br>Increase in evaporator heat extraction with condensing water vapour (Grigg and McCall 1988);<br>Increased size low temperature radiators (Brown 2007; Grigg and McCall 1988);<br>Larger than conventional water cylinder and indirect coil to prevent rapid cycling (Brown 2007; Grigg and McCall 1988) | Reduced airflow caused by frosting of evaporator (Chen and Guo 2009);<br>Operation of defrosting cycle (Grigg and McCall 1988);<br>High sink temperature increases temperature lift (Grigg and McCall 1988);<br>Part load cyclical operation, when heating demand met (Grigg and McCall 1988);<br>TRV's can over-restrict flow rate (Grigg and McCall 1988) |
| Property design and construction related | Increased thermal insulation (Wang *et al.* 2009);<br>Large WWR designs (Wang *et al.* 2009);<br>South orientation increases solar gains (Wang *et al.* 2009; Persson *et al.* 2006) | Heating load increases with WWR due to higher heat losses (Wang *et al.* 2009) |
| Building related | | Linear correlation between increased household size and energy use (Santin *et al.* 2009; Yohanis *et al.* 2008);<br>Increase in room/bedroom numbers (Santin *et al.* 2009) |
| Occupant related | Homes with no children, or working adults (Santin *et al.* 2009; Yohanis *et al.* 2008);<br>10-30% reduction if change in behaviour (Yohanis *et al.* 2008) | Thermostat makes occupant more aware of internal temperature (Santin *et al.* 2009; Yohanis *et al.* 2008) |

In relation to occupancy, NHBC Foundation (2009) and Santin *et al.* (2009) suggested that important characteristics in determining energy use include occupant age distribution, number of occupants and their occupation pattern, hot water/appliance usage behaviour, household income and if rented or owned. The influence of occupant numbers and age on energy usage was emphasized by Yohanis *et al.* (2008), who also explained that homes with no children or working adults consume less energy than properties occupied by families or older residents. Santin *et al.* (2009) supported this claim by stating that day-time occupation leads to more energy consumption than unoccupied homes or intermittent presence of occupants within the home.

## METHOD

This research was carried out through a combination of a critical literature review and a case study. The case study was undertaken with a medium-sized UK housebuilding company, who utilized ASHP for low carbon new-build homes. The selection of the company reflected a 'convenience sampling' strategy (Bryman 2008), as the researcher has a long-term research collaborative relationship with the firm. Through such collaboration, the company was also keen to gain extensive and practical knowledge in low carbon construction, and as Osmani and O'Reilly (2009) suggested, by doing so, developers could meet enhanced construction requirements more cost effectively. The operational efficiency of ASHP was investigated within the context of a 36 unit new-build low carbon homes development in East England. Initially, semi-structured interviews were carried out with the senior management team of the firm, which aimed to explore their underlying considerations for adopting and utilizing ASHP. This was complemented with the analysis of documents provided by the company and available at its website. After a site visit and an interview with the site manager, a postal questionnaire survey was developed, drawing on the literature and interim results from the interviews. The questionnaire was sent to the residents of 21 homes which were installed with an ASHP and occupied. The questionnaire consisted of 21 questions, addressing dwelling specifics, occupancy details, ASHP utilization (e.g. ASHP electricity meter readings), and residents' values and perceptions of ASHP usage. With a reminder, eight useable completed questionnaires were received, generating a 38% response rate. These eight dwellings generally represented the characteristics of the development. Descriptive methods were used to analyse the quantitative data of the occupied homes space and hot water heating energy consumption in comparison with a 'prototype' home. The qualitative analysis involved the process of coding and identifying themes and patterns (Naoum 2007).

## RESULTS AND ANALYSIS

### Performance of ASHP in the 'prototype' home

The 'prototype' property on the site, which was used as the site office and show home, was installed with an ASHP system. Performance of that ASHP has been monitored and analysed by the company, using the COP figures provided by the manufacturer, for publicity purposes and achieving a better understanding of using such technology. For the measured period from September 2007 and June 2009, results show that the ASHP system saved 42.3% carbon dioxide emissions compared to oil and 27.7% for gas. However, it is estimated that the carbon dioxide emissions savings would reduce to 22.2% for oil and 4.1% for gas if the COP of 187.5% specified in the SAP 2005 was used. However, interpreting such results should take into account the facts: that the ASHP in the show home was constantly operated at fixed settings, 2.1 mean TRV (Thermostatic Radiator Valve), with a dhw (Domestic Hot Water) usage of 6 times per day, and that the show home was occupied during the day only. Therefore, the show home was not occupied as a 'real' home, and the data collected was primarily dictated by the space heating operation. The results are therefore not accurately representing dhw usage or taking into account influence by occupation variables. Nevertheless, the developer argued that the site office is located in the garage, adding a 23.86m$^2$ of space heating demand, of which the extra-large low-temperature radiator was of sufficient load to compensate for the reduced draw from the dhw cylinder. Also, the space heating demand included the un-insulated garage containing 9.45m$^2$ more glazing than normal. Whilst this rough fix may approximate the general level of consumption, the reliability of the exchange appears not to have been quantified, which could distort the company's data analysis. Indeed, the operation of the heating system in an occupied property would reflect many occupation variations, which is analysed below.

### Performance of ASHP in occupied homes

Drawing on the literature and the specifics of this study, the analysis of ASHP operational efficiency and energy consumption was designed to take into account the factors including; heated floor area, number of occupants, number of bedrooms, dhw usage, dhw temperature and TRV settings for space heating. However, the data collected for this study to date (Table 2) suggests broad variations of occupancy behaviours which, coupled with the small dataset available for this reporting, rendered the use of advanced statistical analysis less meaningful. Despite these limitations, a strong positive linear correlation (r = 0.867, p = 0.057 (two-tailed) or 0.029 (one-tailed)) was observed between energy consumption and heated gross internal floor area of the surveyed occupied homes. Also, the cross comparison indicates a trend that energy consumption decreased when there were three or more occupants, whilst the energy use increased with the presence of occupants during the day.

*Table 2: Dwelling details and energy consumptions*

| Dwelling | Plot 2 | Plot 3 | Plot 8 | Plot 12 | Plot 13 | Plot 16 | Plot 24 | Plot 36 | Prototype |
|---|---|---|---|---|---|---|---|---|---|
| Dwelling type | D | D | D | D | D | SD | SD | SD | D |
| Heated GIA ($m^2$) | 100.3 | 182.6 | 98.0 | 115.6 | 129.5 | 72.1 | 72.1 | 72.1 | 153.3 |
| External wall | CW | CW | CW | CW | CW | TW | TW | TW | CW |
| No. of bedrooms | 4 | 6 | 3 | 5 | 4 | 2 | 2 | 2 | 4 |
| No. of occupants | 4 | 3 | 2 | 2 | 5 | 1 | 2 | 3 | 2 |
| Ave' kWh/day | - | 58.36 | 21.97 | - | 13.57 | 7.82 | - | 15.55 | 30.70 |
| Estimated annual kWh | - | 21300 | 8019 | - | 4953 | 2855 | - | 5674 | 11205 |
| Annual kWh/sq m | - | 116.7 | 81.8 | - | 38.3 | 39.6 | - | 78.7 | 73.1 |
| dhw temp' | 42 | 50 | 42 | - | 16 | 45 | 45 | 45 | 45 |
| Radiator temperature | WD | WD | WD | WD | 22 | WD | - | 20 | WD |
| Mean TRV | 3.0 | 3.6 | 2.4 | 2.3 | 4.5 | 3 | 2.5 | 2.4 | 2.1 |
| Mean dhw usage (no.) | 33 | 16.5 | 30 | 10.5 | 28 | 17.5 | 25 | 46.5 | 6 |

*Key: Detached = D; Semi-detached = SD; Conventional cavity wall = CW; Thin joint wall = TW; Weather dependant = WD*

A detailed examination of the energy and performance data helps with understanding the seeming discrepancies between the dwellings reflected in the dataset. The energy data of Plots 13, 16 and 36 was based on part year samples that exclude a full heating season. This restriction explains why the average kWh/day values of these plots were significantly less than that of Plots 3 and 8. In particular, the energy consumption of Plot 16 was estimated using a three month period during the early heating season (September to December). In addition, although Plot 16 used 37% less dhw than its identical Plot 36, it operated the ASHP for heating purposes significantly longer. Conversely, Plot 13 had the lowest temperature lift and energy consumption per sq m as well as the least TRV restricted flow rate. These results suggest that the dominance of the dhw operation during the consumption measurement period makes the temperature lift more significant. Although these results appear theoretically accurate, the reported dhw temperature of 16 degrees Celsius of Plot 13 appears dubious. Among the eight occupied homes, Plot 3 represented the highest annual electricity consumption. However, its highest temperature lift and second lowest dhw usage could potentially offset the effects. The magnitude of Plot 3's energy consumption could be attributed to any higher levels of lighting and appliance usage and/or that the occupants might work from home. Finally, Plot 8 reflected an 'average' in terms of the TRV settings, dhw usage, and annual electricity consumption. However, even with a three degrees Celsius reduced temperature lift, ASHP efficiency could be reduced with flow rate based on the 2.4 mean TRV settings.

**ASHP in the 'prototype' property vs. in occupied homes**

The measure kWh/sq m is used for comparing the energy consumption between the prototype and occupied homes, due to the varying heated floor areas. The results show that the energy consumption of occupied homes was generally consistent with that of the show home (73.1kWh/sq m), on the basis of adjustments to account for full occupation and appliances and lighting usage. The energy use profile of the show home was particularly similar to Plot 8 (81.80kWh/sq m) which was occupied all day by two adults with similar TRV and temperature settings, measured over a long duration. Also, when adding the prototype home to the dataset, the correlation between energy consumption and floor areas remains similar but becomes more statistically significant ($r = 0.852$, $p = 0.031$ (two-tailed) or 0.016 (one-tailed)). These results, together, suggest that the operational efficiency of the ASHP system installed in the 'prototype' property was consistent with those in occupied homes.

**ASHP efficiency and COP figures**

According to the show home's SAP 2005 results, the 'primary energy' (excluding appliances and other equipment energy usage) equals 19,529kWh/year or 152kWh/year/sq m. However, the total property energy consumption meter readings collected by the company (including all energy consumption even though non-ASHP usage is deemed not representative of full occupation) equals 11,205kWh/year or 73.1kWh/year/sq m. As reviewed early in the paper, the SAP calculation is based on an ASHP efficiency of 187.5%, which has been reduced from 250% by 25% due to the use of radiators (Building Research Establishment 2009). However, the analysis by the company was based on the use of COP figures ranging from 3.04 to 4.92 over the full measurement duration averaged at approximately 4. Considering that SAP predicted 2634kWh out of the total for 'electricity for lighting', it seems unlikely that a 43% difference in total consumption would be the result of the unoccupied nature of the show home. Therefore, the figures suggest that, based on the company's operational performance data, the manufacturers' ASHP efficiency values appear a more reliable indication of actual performance than that of SAP 2005. Clearly, SAP 2005 disadvantages the ASHP efficiency. However, the proposed SAP 2009 amendments may reflect the actual in-use performance of ASHPs in new-build homes more accurately.

**Householders' values and perceptions of using ASHP**

The residents held a 'neutral' to 'slightly positive' attitude towards the user-friendliness of TRVs, but were quite negative for the ASHP programmer. The developer also described the ASHP programmer as 'the most complicated'. These views suggest that the ASHP controls are complicated and function as a barrier to its utilization.

Visual impact was perceived 'neutral', with spatial being less impacting. This supports the prediction that the unfamiliar commercial appearance of the external unit could sway residents' perceptions. Conversely, BERR (2008) ranked resource constraints as a 'medium' barrier. Also residents stated that they would both optionally purchase and recommend a property installed with an ASHP. Apparently, the residents were intolerant of the noise issue of utilizing ASHP. However, considering that the sound level, approx 61dBA for an ASHP external unit, is comparable to a 'normal conversation' (McMullan 2007), other factors such as vibration must be jointly accountable. Differences in the isolation mounting techniques utilized confirmed this.

The residents were predominantly ‘satisfied’ with both the ASHP reliability and maintenance costs. However, it is questionable if some properties have even required maintenance considering the short duration of occupation. Interestingly, the respondents who have previously owned a gas or oil heated home were ‘satisfied’ or ‘very satisfied’ with ASHP regarding their maintenance costs. Such result indicates that the residents perceived ASHPs to be more reliable than gas or oil boilers for maintenance. Even though the integration of ASHP was not considered as a positive factor during purchase, the value of ‘green’ issues was regarded ‘important’. The residents primarily rated the ASHP economy as ‘neutral’ to ‘very economic’, and then described ASHP as ‘energy efficient’. These mixed responses suggest that there was little consistency in ASHP understanding among the occupants, which supports the observations made by BERR (2008). As a result of this barrier, home owners are deemed less likely to broaden their choices and contemplate utilizing renewable technology.

# DISCUSSION

This study identified a strong positive linear correlation between energy consumption and heated gross internal floor areas of dwellings. Such correlation confirms the linear correlation between household size and energy use observed by Yohanis *et al.* (2008) based on a sample of 27 dwellings. Yohanis *et al.* (2008) also stated that electricity consumption decreases per occupant as occupant numbers increase. However the data collected alternatively shows that consumption did not decrease until there were three or more occupants in the dwelling. Nevertheless, it should be noted that the variability of the ASHP and TRV settings are not taken into consideration in the analysis, which may influence the results. Furthermore, Santin *et al.* (2009) and Yohanis *et al.* (2008) both identified that energy consumption increased with the presence of occupants during the day. Due to the progressive refinement of the postal questionnaire survey, the property occupation pattern was only asked in the context of the ‘typical’ pattern. Therefore, useful data was only ascertainable from four out of the eight homes investigated, which limits the comparability of the results.

The influence of the number of potentially heated rooms/bedrooms increasing the demand for space heating was highlighted by Santin *et al.* (2009). However, due to the fact that only two responding households have occupied their homes for longer than a year, no valid comparison could be made. Likewise, the same conclusion can be drawn that homes with no children or working adults have reduced electricity consumption (Yohanis *et al.* 2008).

In terms of the ASHP efficiency debate, Hughes (2009) reported that it is unclear what difference the proposed ASHP efficiency and emission factor amendments to SAP 2009 will make to ASHP legislative performance. Initial calculations carried out in this research using the company’s data revealed that SAP 2009 would produce not too dissimilar carbon dioxide emissions results to their original estimates. However, this is dependent on what COP is agreed on. Therefore, although ASHPs currently only save 4.1% carbon dioxide compared to gas using the SAP 2005 recognized COP, SAP 2009 will theoretically make ASHPs a more effective form of low carbon technology.

## CONCLUSIONS

This paper has examined the adoption of ASHP for low carbon new-build homes, with a particular focus on investigating the operational efficiency of such technology. Despite the many variables and factors influencing energy performance of dwellings and ASHP efficiency, the results obtained from the prototype property as well as a number of occupied homes suggest a strong positive correlation between energy consumption and heated floor areas. The results also provide evidence supporting the claims made by the developer of the monitored ASHP performance in the prototype home that the use of ASHP leads to significant carbon emissions savings over conventional gas and oil boiler systems. Such savings were significant, based on the use of COP values provided by the manufacturers, but are compromised if using the COP recognized in SAP 2005. In this respect, the paper, drawing on the energy cross comparison between the prototype property and occupied homes, observes that the ASHP efficiencies provided by manufacturers and adopted by the developer in their calculations appear to be reliable. The householders were generally positive of the economy, space impact, reliability and maintenance of ASHP, but negative of its visual impact and the noise issues. The majority of respondents were willing to choose and/or recommend a property installed with an ASHP. However, occupants' lack of understanding of efficient ASHP operation was identified as a significant barrier to realizing the full benefits of using such technology. The findings of this paper has provided evidence demonstrating the efficiency benefits of ASHP systems, which contributes to the knowledge of utilizing such technology for low carbon new-build homes. The exploration of the relationships between energy consumption and its influencing factors highlights the complexity of and interactions between design, building and occupancy variables. Future research may explore such relationships in a more statistical manner, drawing on a larger sample of dwellings, in order to contribute to the wider debate on ASHP's efficiency and performance.

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