Ecology of heat pump performance: A socio-technical analysis

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Abstract. The UK government's heat strategy is to reduce emissions from buildings "to virtually zero by 2050" through a combination of technologies such as heat pumps (HPs). As part of this strategy, it introduced the Renewable Heat Premium Payment (RHPP) Scheme to incentivise the installation of HPs in the residential sector. Using a socio-technical approach and case study method developed by the authors in the field of energy research and building, this paper explores the reasons for variation in performance of HPs supported by this scheme. Twenty-one sites/households were selected for investigation. Due to limited space, this paper does not seek to present all cases, but instead focuses on key insights from five cases that were originally thought to be poorly performing. The findings highlight the complex ecology of a socio-technical system in determining performance. We will show that system performance emerges from the dynamic interaction of monitoring system, heat pump system configuration and occupants' heating practices and heating load factor. Limitations, practical implications and scope for future research are briefly discussed.

Keywords: heat pump performance, ecology, socio-technical.

1 Introduction

The UK domestic sector accounts for approximately 29% of final energy consumption, with space and hot water heat accounting for approximately 80% of this. Enshrined in the sectoral plan of the government's Carbon Plan [1] and Heat Strategy [2], is the goal of reducing emissions from this sector to close to zero through a combination of improved energy efficiency and deployment of low-carbon heating. Heat Pumps are seen as a key technology for achieving this, and the UK government set up the Domestic Renewable Heat Incentive (RHI) Scheme and the Renewable Heat Premium Payment (RHPP) to promote the installation of HPs in this sector [3]. In parallel, it set up a field trial to understand performance of HPs installed under the RHPP scheme. This trial collected data for 700 of the c.14,000 HPs installed under the scheme, forming the largest HP field trial undertaken in the UK to date. Performance in the field is critical in terms of the economic competitiveness of the technology, its acceptability to dwelling owners and occupants, and to enable the UK Government to demonstrate compliance with the UK's target for renewable heat under the EU Renewable Heat Directive [4]. Currently, performance of HPs is defined by two indices, the coefficient of performance (COP) and the seasonal performance factor (SPF). The Renewable Heat Incentive Scheme Regulations [5] require that both air source heat pumps (ASHPs) and ground source heat pumps (GSHPs) should attain COP=2.9 and SPF=2.5 at boundary H4, to qualify for support under the scheme. A team led by the second author of this paper was commissioned to analyse remote monitoring data from the field trial and to undertake detailed case studies of a sample of 21 installations using a socio-technical approach with the aim of improving understanding of remote monitoring systems, quality of metadata, reasons for variations in performance, and occupant satisfaction with their HP systems. Due to limited space, this paper does not seek to present all cases, but instead focuses on key insights from five cases that were originally thought to perform poorly.

2 Research design and methods

The present authors' previous research in building performance has shown the necessity of taking a socio-technical system perspective to empirical investigation of the performance of energy technologies in the field [6]. This has resulted in the development of a socio-technical Case Study Method to collect and integrate data from people and technical systems [7] that are interconnected, mutually adaptive, and co-constituted. Below is a brief outline of the design and methods used for data collection, analysis and interpretation. A full report on the RHPP Field Trial case studies is available on-line [8].

2.1 Sampling strategy and collection of data

Based on statistical analysis of remote monitoring data, 117 householders and 31 Registered Social Landlords (RSLs), representing a range of HP performances and geographic location across the UK, were identified for initial contact. Positive responses were received from approximately 1/3 of the householders, and almost half of the tenants contacted by RSLs. Following a further round of selection, occupants of 21 dwellings, 7 under the ownership of RSLs, and 14 owner-occupied, were recruited to take part in case studies. Site visits of 2-3 hours duration were made by a team that included one technical researcher and at least one social researcher, who recorded detailed characteristics of each dwelling, configuration and arrangements of HP systems and interviewed occupants about their life-style, perceived thermal comfort in relation to the installation and operational experience of and satisfaction with the HP during a room-by-room "walk-through" of the dwelling [8:42].

2.2 Analysis

In the first instance, both quantitative data and qualitative data were entered into a master matrix. Analytic matrices were then constructed [8: App.1] based on an investigative logic of HP performance. This analytic framework gave primacy to thermodynamic constraints, expressed qualitatively by the equation:

$$COP \approx 0.5 \times 330/\Delta T$$

(where ΔT is the difference between the HP's source and output temperatures), to the configuration of system components and their interactions with built-form and heat loss taken from Energy Performance Certificates (EPCs), to impacts of human behaviours such as commissioning of systems by installers/or occupants themselves, and to occupants' operating strategies in the context of lifestyles and costs.

Table 1 below summarises the 16 cases in terms of types of HPs and their performances. Analysis was initially performed on a sub-sample of 10 cases selected from the 21 cases – these are arranged horizontally in Table 1. Because this sub-sample included only a single RSL dwelling, the sub-sample was then expanded to include all 7 RSL dwellings in the 21, bringing the total number of cases subjected to detailed comparative analysis to 16. The additional 6 cases are arranged vertically in Table 1. Estimates of SPFs for all systems were refined during the analysis.

Table 1. Cases classified by heat pump type, SPF band and tenure.

"well performing" heat pumps (SPF > 2.5)
"poorly performing" heat pumps (SPF < 2.5)
Heat pumps reclassified as "well performing" following analysis
RSL-owned dwellings shown in *italics*.
"AS" denotes air source and "GS" denotes ground source heat pump.

									CS02 AS
									CS03 GS
									CS04 GS
									CS05 GS
									CS06 AS
CS18 GS	CS13 GS	CS19 AS	CS14 GS	CS20 AS	CS16 GS	CS12 GS	CS15 GS	CS09 AS	*CS07 AS*
									CS08 AS

3 Factors influencing performance

3.1 Monitoring systems and data quality

Seven "poorly performing cases", CS02, CS03, CS07, CS09, CS12, CS15, CS16, were initially suspected by the quantitative team of having monitoring system issues. A combination of revised algorithms for automatic selection of monitoring data and analysis of case study data led to SPFs for CS07, CS09, and CS15 being revised upward to above SPF=2.5, leaving only four poorly performing cases.

Metering issues were one of a number of problems that affected CS07, including a report from the occupants that their HP had suffered a “blow out” which was corroborated by inspection of the monitoring data. These problems appeared to be resolved following replacement of the faulty external unit. Monitoring issues were also suspected in CS09; monitoring data indicated that the HP exhibited a persistent but unexplained reduction in mass flow in the primary heating circuit as recorded by the heat meter flow sensor. However, in the interview, the occupants reported that there had been a flat battery in the monitoring system in the initial period following installation which, once detected, had been replaced. The SPF for this system was re-estimated based on data that was deemed not to have been affected, resulting in reclassification as well performing. CS15 had a monitoring issue due to faulty installation of equipment, but this was corrected after its discovery.

> “When sensors were placed, [the] fitting was wrong – it was running backwards for a long time – then they came back and altered it; they’d put the sensors on the wrong pipes; this happened [maybe] around 18 months ago”.

CS12 was suspected to have potentially serious and unresolved problems with the monitoring system, which were confirmed during the site visit (see section 3.2). Metering issues were suspected in CS16 due to a low SPF, but subsequent analysis suggested this was better explained by the low load factor of the heating system (see section 3.3) which in turn arose from the occupants’ heating practices. Finally, metering issues were also suspected in CS13 and CS18, due to data showing heat output with no electricity input for short periods.

3.2 System configuration and heating practices

The five well performing cases, CS13, CS14, CS18, CS19 and CS20, with SPF well above 3 seemed to have well-insulated systems. Well-insulated internal pipework was also found in two of the reclassified cases, CS15 and CS09, suggesting an association with performance.

Metering data for CS09 indicated the presence of resistance heating for domestic hot water. This appears to correspond to CS09’s everyday heating practices. As a couple of retirees, the occupants lived mostly in the kitchen during the day-time, retreating in the evening into a small study to watch television; hence the living room was rarely used. The temperature in the kitchen tended to be set at 18°C, as “movement [of] the sun & heat from cooking [would] make it comfortable [enough]”. The kitchen also housed a large electric oven (an Aga). It is possible that the occupants had been using the electric Aga to provide hot water but were not aware that this might be costly.

Believing that they could keep themselves comfortable with lower costs, occupants of CS09 controlled the temperature in the dwelling by switching their HP on and off and by altering its flow temperature. They said that they did not find the temperature so controllable using the thermostat. The researchers observed that the thermostat was sited in an unheated lobby with a door often closed between the lobby and the living space. This might have caused a higher than set-point temperature in the rest of the dwelling, prompting the occupants to adopt the on-off control strategy to keep the temperature down. From the documentation, less-than-adequate airtightness of the dwelling was discovered by pressurisation test at the time of installation of the HP. This might have added to the poor performance recorded at the outset.

CS12 was another poorly performing case with SPF initially estimated as 0.7. The heating system was characterised by un-insulated pipework (see Fig. 1 below).

Fig. 1. CS12 – Uninsulated pipework associated with heat pump.

CS12 was a GSHP. Its hot water cylinder was housed in a cupboard within a heated utility room. There was underfloor heating installed on the ground floor but radiators upstairs. Preliminarily, it was thought that internal uninsulated pipework should not affect performance. However, CS12's room thermostat was in the kitchen immediately adjacent to the heated utility room. The room thermostat in the kitchen could have been affected both by heat gain from cooking and uninsulated pipes in the adjacent utility space. Either factor might in turn have increased the tendency of this system to cycle.

Monitoring data showed that heat demand for space and water heating were below electricity input in every month for two consecutive years. An inquiry was made into whether the data could be subject to metering error. Two features of the monthly mean electricity and heat demand plot suggest it might have been. First, the extreme seasonality of hot water demand and the persistence of space heating demand through the summer, suggested that there may have been a misallocation of total HP heat output between space and water heating – this appeared likely in the light of a photograph taken on site of the monitoring installation (Fig. 2) showing an auxiliary temperature sensor on one of the primary circulation pipes, which had been installed with insulation between it and the pipe. This could explain why the level of both space and water heating recorded were implausibly low, even in a well-insulated dwelling with a single occupant. The total heat output of the HP in January was sufficient to raise the internal temperature of the dwelling by about 4°C. Without other sources of heat, this would have brought the mean internal temperature in January to around 8°C. Solar gain in

January is negligible, and internal free heat gains would have been unlikely to add more than a few degrees centigrade to the internal temperature.

Fig. 2. CS12 - pipework showing insulation between temperature sensor and pipe. The auxiliary temperature sensor for the heat meter is just right-of-centre in a pocket. Source, BRE.

The site visit took place in December. Researchers observed that set-point temperatures of most room thermostats in this dwelling were in the range 17-18°C. Internal temperatures were not recorded, and it was therefore difficult to determine whether the set-point temperature was reached or not. But the occupant stated that she was "comfortable". The manufacturer's documentation showed the system installed in this dwelling was fitted with either a 6 kW or a 9 kW "additional electric heater". Given doubts about the monitoring system, it was not possible to determine from the data collected what proportion of HP output was produced by electric resistance heating. However, plotting heat output from the HP against electricity input from available physical monitoring data, showed that a proportion of the heat output of this system was derived from resistance heating, and that a proportion of the electricity input resulted in no measured heat output. This is consistent with a statement made by the occupant during interview that the booster had, probably accidentally, been turned on by a plumber, but it was not until a "huge bill" (around £1100/year) arrived that she realised there was a problem. The occupant reported that she tried and managed to switch the immersion heater off on the control panel with the help of her father and the manual. This illustrates the complex issues involved in measuring HP performance. The presence of multiple problems - a low thermostat set-point, and the accidental triggering of resistance heating - might all have played a part in lower performance.

3.3 Low load factor and performance

CS16 was a newly built farm house of 314 m^2 gross floor area. The EPC showed high ratings for all aspects of the dwelling and its systems, and an overall EPC rating of A. But the monitoring data showed an SPF of only 1.7.

In an attempt to understand the reasons why this HP performed poorly, the researchers first checked whether the design capacity of the HP (12 kW) was adequate to meet the heat demand of the dwelling. The calculation suggested that there was sufficient capacity in the HP to heat the dwelling down to external temperatures of around 0°C. Attention then turned to the monitoring data. It was noted that the envelope of HP electricity consumption dropped abruptly by roughly 3 kW in late March 2014, coupled with a drop in the system output temperature. A possible explanation is that the booster heater was turned off at this point.

Inspection of the mean monthly energy flows in CS16 prompted further questions. The split between DHW and space heat changed by a large amount between the two years. DHW went up. Space heat went down by about the same amount. Total heat output stayed roughly the same.

From the analysis of the interview data, there appeared to be a range of issues affecting performance, driven by occupant changes to their control strategy. Despite having photovoltaic panels installed under a generous feed-in-tariff (FIT), the occupants did not feel that these payments were sufficient to offset the cost of their energy bill. They reported that since the HP had been installed, their electricity bill "goes up hugely during the winter quarter", to around £720 in the 2015 winter quarter and approximately 1/3 of that in the 2015 summer quarter. They estimated their annual bill was approximately £1900 that year. In order to save money, they decided to use the HP only to provide background heating and tried out different ways to heat the house. These included: turning down most of the room thermostats to 16°C (exceptions were the hallways and *en suite* bathroom, which were set at 21°C); having their electric oven (an Aga) set to its "snooze" setting (110°C, with a corresponding continuous electricity consumption of approximately 600 W) to provide background resistance heating in the living room-kitchen; and using two wood burners (one in the snug and one in the lounge) to supplement the heating every night in winter, and during the day if it was cold. Moreover, the dwelling was a farmhouse and the occupants' life as farmers might also help to explain how lower temperatures were tolerated as a result of wearing warm clothing inside the house. It was observed that they and their two dogs spent most of their days in-and-out of the house. Despite sophisticated zoning, their external doors were opened and shut quite often, making precise control of temperature in the house difficult. This, coupled with a rather high electricity consumption resulting from frequent use of appliances such as a tumble drier, a dishwasher and a washing machine as well as electric power showers, makes it unsurprising that their electricity bill was high. But, in the light of a growing awareness of the consequences of their lifestyle, the occupants had given up trying to control their internal temperature using room thermostats and were instead "experimenting" with using secondary heating devices such as the two wood-burners and the oven mentioned above. It is likely that the use of the Aga, the power showers, tumble dryer and the wood burning stoves, none of which were controlled by a room thermostat, would have restricted the operation of the HP during the monitoring period. All of this begins to explain why the HP delivered less than 10,000 kWh/year of heat, less than 40% of the more than 26,000 kWh/year estimated by the EPC assessor for this house.

Further light was shed on the poor performance of CS16 by a comparison with two other cases with similar physical characteristics. All three dwellings were over 290 m^2 floor area (roughly 3.5 times UK mean floor area per dwelling, and the largest among the 16 case studies). The estimated heat annual demands recorded on the EPCs for these houses were: CS14, 16,800 kWh/a; CS16, 26,300 kWh/a; CS18, 20,400 kWh/a.

The GSHP installed in CS14 was rated at 12 kW; CS16 and CS18 were fitted with GSHPs from the same manufacturer. All systems had an integrated auxiliary heat unit, to back up and supplement the output from the HP. All three dwellings had underfloor heating. Based on the monitoring data, the mean heat demands of CS14 and CS18 were shown to range between 3.3 and 7 kW in the period from November to February, yet CS16's mean heat demand was less than half this, between 1.3 and 2.7 kW. Setting aside the possibility of issues with data logging for the moment, the question is whether the low heat demand of CS16 might have contributed to the low SPF. This working hypothesis was put to the test by plotting the monthly mean COP versus load factor for these three cases (Fig. 3).

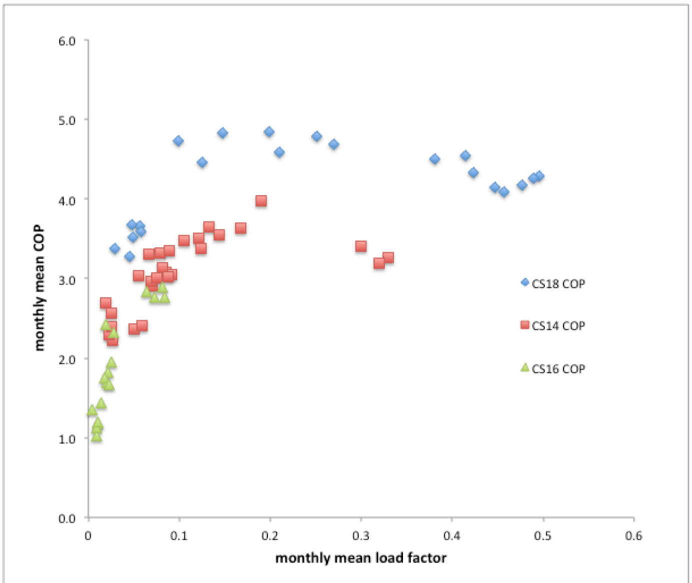

Fig. 3. COP versus heat load factor (monthly means) CS14, CS16 & CS18.

The graph suggests that:

- the low SPF of 1.7 for CS16 is in fact likely to be correct and can be explained by the low heat load factor in this dwelling: the HP performance profile plotted in this way is more or less indistinguishable from the installation in CS14, which has an SPF of 3.5;
- monthly COP rises monotonically with heat load factor up to a load factor of 0.3 for CS14 and to 0.4 for CS18 - at higher load factors, monthly COP falls, perhaps suggesting the onset of electric resistance heating.

Note that the CS16 GSHP had a fixed speed compressor, but it is not known whether ground loop and primary circuit circulation pumps were fixed or variable speed, both of which would tend to reduce part load performance.

Thus, it appears that efficiency is a function of load factor, and that it may therefore be affected by behavioural and social factors, such as a requirement to save energy or reduce high fuel bills, or the use of secondary heating not metered by the HP monitoring system.

4 Discussion

Using a socio-technical approach that aims to go beyond simply understanding either users' behaviours or the technical system, this paper attempts to illustrate the complex ecology of interactions and relationships within and between both systems in determining performance. The metric of HP performance is itself the product of a socio-economic-technical system (the Renewable Energy Directive) that sets the boundary between good and poor performance. Each HP's operational performance is determined from data collected by a monitoring system, the performance of which depends on quality of installation. The detailed configuration/installation (i.e. arrangements of physical components) of the HP in the dwelling prefigured occupants' heating/ventilation practices. These determine the heat load, which impacts on the HP performance. This in turn appeared to reinforce the original behaviour of the occupants. The plot of performance against heat load factor provided a way to encapsulate the dynamic relationships between a constellation of contextual factors, such as thermal efficiency, lifestyle, perceived comfort, occupants' practical understanding and skills in controlling the HP through manipulating thermostat and flow rate or the use of non-thermostatically controlled secondary heating, as well as unintentional human decisions that resulted in an increase of electric resistance heating. It appears that unexpectedly high electricity bills could be a cue for remedial measures, triggering actions that led to reduced heat-load, and beginning a positive feedback cycle.

If we take seriously what this study has revealed, we will have to approach policy implementation, monitoring and evaluation of low carbon heat technologies differently. While SPF might be a useful metric for determining the overall success of policies and programmes, the complex paths of learning by which performance is achieved and sustained cannot be ignored. It is possible that an overly simple conceptualisation of uncertainties around HP performance, reflected in energy models, might have been one factor contributing to the recent scaling back of UK Government support for the RHI programme. A richer understanding of performance in the real world that captured the process of inter-adaptation between technology and people [6] might help to avoid such outcomes in the future, and lead to more innovative policy and more effective interventions to improve performance. For example, many of the issues raised in this paper could be addressed by reconceptualising heat as a service and supporting the development of customer care packages.

It has not been possible in this short paper to expand on the theoretical and methodological developments that have underpinned the analysis, but references have been given. However, the socio-technical analysis presented here challenges the conventional separation of physical and social disciplines in applied energy research. A research programme that opened opportunities for multi-disciplinary collaboration would be one way to improve the environment for learning.

5 Acknowledgements

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Commentary describing changes made in response to reviews.

1. In response to Reviewer 1's request that we make clearer the policy implications of our work, we have added a paragraph "If we take seriously what this work has revealed…" on page 10.

2. Reviewer 1 requested a brief discussion of the contribution of this study to research carried out in the US regarding residents engagement with heat pumps. We have encapsulated this in our revised discussion of the power of the socio-technical case study method to yield rich data on the interaction between occupants and HPs, and the potential for new business models to support interactive adaptation.

3. In response to Reviewer 2's request for reformatting, we have right justified throughout.

4. We have corrected a typo on p3 identified by Reviewer 2, and taken the opportunity to address issues of wording throughout the paper. Numbering of figures is now corrected and captions are correctly formatted. Careful re-editing has enabled us to keep overall length to 10 pages.

5. "in order to saving money" (p7) has been corrected.