Domestic demand-side response with heat pumps: controls and tariffs

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ABSTRACT

Electric heat pumps feature prominently in projected energy transitions in the UK and elsewhere. Owing to their high electricity consumption, heat pumps are viewed as important targets for demand-side response (DSR). Findings are presented from a field trial of a new control system that aims to optimize heat pump performance, including under time-varying tariff conditions. The trial involved monitoring 76 properties with heat pumps, but without dedicated heat storage; 31 of these received the control system. Interviews were conducted with a subsample of 12 participants. The controller successfully evened out electricity demand over the day (reducing the evening peak), but this was associated with increased late night and daytime temperatures. Interview participants reported some disturbance owing to overnight heating and noise, as well as usability issues with the controller interface and hardware. These issues present risks to the future acceptability of such systems. While the system delivered short-term demand reductions successfully, longer-term demand shifting risked causing unacceptable disturbance to occupants. Future control systems could overcome some of the issues identified in this pioneering trial through more effective zoning, using temperature caps or installing dedicated heat storage, but these may either limit the available flexibility or be challenging to achieve.

Introduction

The potential for demand-side response (DSR) to contribute to the delivery of a decarbonized energy system is widely acknowledged (DECC, 2015). Domestic demand flexibility can, in theory, be delivered with minimal impact on the household's enjoyment of energy services through the use of energy storage. The provision of flexibility using electric heat pumps is one of the more attractive options for domestic DSR, mainly due to their order-of-magnitude greater electricity demand relative to most other home appliances. Even where dedicated heat stores are not available, by using the thermal inertia of the building fabric and heating system it is possible for heat pumps to be cycled off and on with a limited effect on internal temperature and, it is hoped, occupant comfort. This flexibility can be delivered automatically, without occupant intervention, and therefore is likely to elicit a greater, more reliable and more sustained response than relying on building occupants to respond manually (Frontier Economics and Sustainability First, 2012).

A large number of modelling exercises have attempted to put a value on this demand flexibility, some of which are discussed in the literature review of the following section. To highlight one example, a recent National Infrastructure Commission (2016) report for the UK government projected £8 billion saving could be delivered for consumers from a smarter energy system that used flexible demand alongside storage and interconnection. In the absence of evidence on real-world performance and the role of consumers, many of these projections assume that energy storage will perform according to its theoretical maximum. In order to deliver on this promise, new technology and changes to operational regimes will be required. Not only must the technology operate as planned, but also it must be taken up and accepted by occupants on a large enough scale. Therefore, there is a danger that the projections being made are overstating the potential contribution as well as an urgent need to understand and address any barriers to optimal performance. This is the area this paper aims to address.

This paper draws on the findings of a field study carried out in the south-west of England over the winter of 2014/15. The field study deployed a new control system for heat pumps that aims to provide a user-friendly interface for consumers and optimize heat pump performance generally and in response to DSR signals, thereby

providing the opportunity for coordinated control of heat pumps via the internet. Importantly, there was no dedicated thermal storage (*e.g.* hot water tanks) beyond the thermal inertia of the building. This is likely to become the prevailing situation in the UK where many hot water tanks are being removed in favour of combi boilers (Palmer & Cooper, 2013). The trial used extensive physical monitoring to test the effectiveness of the new control system, combined with in-depth interviews with a subsample of participants to discover whether it also worked for them.

Analysis of the data presented in this paper provides insights into the impact and performance of this type of automated control systems whose deployment is an important enabler of DSR. The paper also addresses the likely real-world performance of demand shifting using heat pumps in the UK.

The paper is structured as follows. The next section briefly reviews the relevant modelled and empirical findings from the literature relating to heat pumps and DSR. The case study and trial methodology are then described, followed by an integrated discussion of the physical and social findings. Implications are subsequently drawn for both industry and policy.

Demand-side response (DSR) with heat pumps: previous studies

The benefits of using demand flexibility to reduce the cost of operating electricity networks have been widely explored in the literature, with potential value typically assessed using various modelling techniques. Fischer and Madani (2017) have conducted a comprehensive review of modelling studies in this area.

A range of modelling exercises has been reported from the building to the national scale. A number of studies have investigated demand shifting in dwellings incorporating some form of buffer tank or thermal storage. Hong, Kelly, Richardson, and Thomson (2011) found that shifts of up to 6 h were possible in well-insulated dwellings with a 500 litre tank; however, Kelly, Tuohy, and Hawkes (2014) found that a 1000 litre tank would be required in similarly well-insulated dwellings. Arteconi, Hewitt, and Polonara (2013), meanwhile, found that an 800 litre tank could only deliver 1 h of demand shifting in poorly insulated dwellings. As discussed below, buffer tanks are currently not commonly installed alongside heat pumps in UK dwellings.

Turning to the potential for energy storage at the national scale, Barton et al. (2013) investigate the potential for demand-side participation under a number of future scenarios. Mathiew, Koch and Callaway (2012), meanwhile, focus on thermal storage and

investigates the use of aggregate control of thermostatically controlled loads to absorb wind energy. Similarly, studies by Barrett and Spataru (2015) used the DYNEMO model to illustrate the potential for domestic demand shifting and heat storage to play a part in optimizing the operation of the energy system as a whole with active, centrally managed control. Kreuder and Spataru (2015) focus on the use of heat pump-demand shifting to reduce demand peaks and identifying potential to cut peak load growth by two-thirds.

The UK government has commissioned a number of studies on the economic value of demand shifting at the national level. Redpoint and Element Energy (2012) assessed the value of domestic load shifting under various mixes of tariff scenarios. Demand shifting of domestic heat pump demand is modelled in a very simple manner, assuming the heat pump can be switched off for 3 h during peak periods with demand supplied by a thermal store; consumer interaction is not considered. This store is charged directly in advance of the peak, which coincides with peak industrial and commercial demand. As the authors point out, this issue could be addressed with more intelligent control of the heat pump and store.

Pöyry (2010) also modelled demand flexibility in domestic heating, assuming that sufficient thermal storage is installed to cover one day of heat use at average demand. A more sophisticated control regime was assumed compared with the previous studies and the analysis showed heat pump demand primarily shifting to overnight periods, except for the coldest periods.

More recently Teng, Aunedi and Strbac (2016) addressed the use of flexible electric vehicle (EV) and heat pump loads to absorb renewable energy. This analysis was based on measured operating patterns of heat pumps and EVs under standard operating conditions. The modelling assumed a 35% reduction in peak demand could be achieved with the use of a 140 litre water tank.

There are two common features of these modelling studies. Firstly, they all assume some sort of additional thermal storage is available beyond the thermal mass of the building fabric. This may not be a reasonable assumption as anecdotal evidence in the UK suggests that additional storage such as buffer tanks are not regularly installed alongside heat pumps. While buffer tanks are important for demand shifting, Green (2012) found the installation of buffer tanks delivered little or no improvement in heat pump performance in field testing of heat pumps under standard operating conditions. Buffer tanks are not mentioned in the UK heat pump-installer guidance (Microgeneration Certification Scheme, 2015) and, indeed, none of the field trial homes considered in this paper has buffer tanks.

Secondly, as Fischer and Madani (2017) point out, they assume perfect control of the flexible heat pump demand without recourse to real-world interactions with consumers or the performance of the technology being deployed. This is understandable, because although there are many trials of demand shifting with heat pumps (*e.g.* the EcoGrid EU, PowerMatching City and eFlex projects discussed below), limited information is available on the performance of demand shifting in the field.

Several authors and studies have published empirical results on the real-world performance of heat pumps under standard operating conditions. For example, the UK Department of Energy and Climate Change (DECC) (Dunbabin & Wickins, 2012) has published a detailed analysis of monitored data highlighting various installation and operational issues such as excessive cycling and energy consumption by defrost cycles found in early heat pump installations in the UK. Any analyses or projections of demand-shifting potential must assume these basic issues have been solved.

Allison et al. (2017) report results from a field trial of a predictive controller in an unoccupied test home with underfloor heating. They found it was possible to achieve bulk shifting of energy demand from the heat pump, but this had a detrimental effect on the efficiency of the heat pump.

Turning to customer acceptance, Friis and Haunstrup Christensen (2016) present a number of important insights from demand-shifting projects in Denmark including the importance of understanding the impact of consumer practices and behaviour as well as the technical issues of energy storage and demand response. They also explore the limits of demand shifting through manual action, which previous work has tended to show is less effective at reducing or shifting demand than when an element of automation is introduced (Frontier Economics and Sustainability First, 2012). Automation, therefore, is likely to be an important enabler of successful demand shifting. However, there is limited international evidence as to how users view living with heat pumps and automated DSR capability. However, given that heating patterns vary significantly from country to country, it is likely that the acceptance of heating control strategies may also differ between countries.

Also on this theme, the Danish eFlex project (Dong Energy, 2012) tested the ability of heat pumps to provide turn-down DSR in response to price or wind-generation signals (or a combination of both), while participants could choose to optimize for cost or comfort. Participants only overrode turn-down events (lasting 1–3 h) 1% of the time, or approximately once in three months, leading the report authors to conclude that 'the customers' comfort zone has not been seriously challenged' (p. 36).

Broman Toft and Thøgersen (2015) conducted interviews with participants of the READY and IMPROSUME trials in Denmark and Norway that involved direct load control of heat pumps. The small sample reported benefits including improved monitoring of heat pump performance and energy use, and disadvantages including lack of hot water and cold thermal discomfort. It is not stated in the reports of either trial whether the pre-heating strategy was using the building fabric as a heat store or if a buffer tank was used.

The contribution of the current paper is to present empirical evidence on the effectiveness and acceptability of demand shifting where the heat pumps uses fabric inertia alone to enable DSR. Analysis of both monitored and survey and interview data gathered in the field study provides new insights in terms of both the technical performance and limitations of this approach and also, importantly, the perceptions of real UK customers.

Field study

The main aim of the field trial was to test the performance of the home energy-management system (HEMS) in controlling electric heat pumps in a field setting. To this end, a combination of physical monitoring, questionnaires and interviews was undertaken. This mixed-methods approach is particularly useful as analysis of the measured data helps both to contextualize and illuminate the questionnaire and interview results. This section describes the HEMS in more detail, the process of participant recruitment, the trial design, and the methods of physical and social data collection and analysis employed.

Home energy management system (HEMS)

The HEMS is based around a small Linux computer (the hub), which is installed in the home and communicates with various sensors and actuators throughout the home and to remote data storage and processing via the internet, allowing data to be stored remotely. The participants in the project were provided with a tablet computer contained in (but removable from) a wall-mounted holder. Figure 1 is a screenshot of the tablet's home page.

In this project, the default occupancy schedule and set-point temperature were input by the installer on installation following consultation with the occupant (s). The schedule could only be changed by calling the HEMS provider and asking them to do so remotely, while householders could use the tablet to make temporary changes to the current target temperature and input temporary 'away' periods. The rationale for this was to keep the actual controller interface as simple as possible.
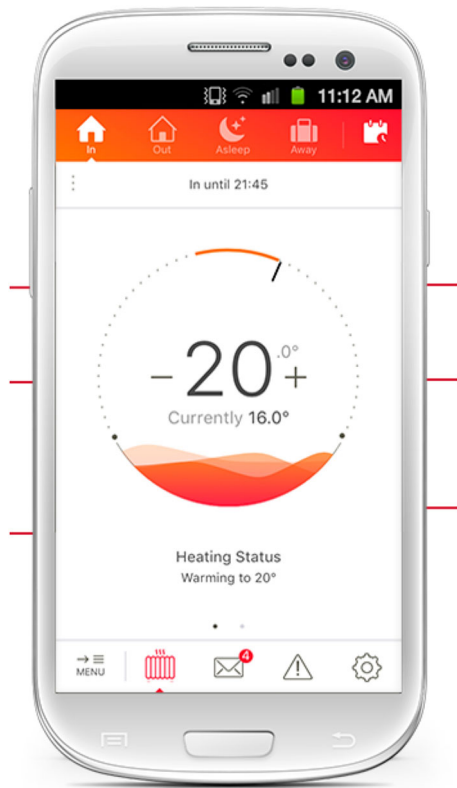
Figure 1. Screenshot of the home energy-management system (HEMS) controller.

As well as accessing this interface via the installed tablet, participants also had the option of downloading a smartphone app providing the same functionality.

The HEMS runs a self-learning, predictive control algorithm that develops a thermal model of the home by observing the building's behaviour in response to heat input, external weather conditions and other factors. This thermal model is used to cost-optimize the operation of the participant's heat pump. This means it should reach the specified target temperatures at the time periods set, but at lower cost than if the algorithm were not being applied. This is a complex, multidimensional trade-off as discussed by Carter, Lancaster, and Chanda (2017), who present modelled outputs from the algorithm. Generally, where energy costs are constant, this means a more constant heat output is maintained compared with simple on/off operation (*e.g.* turning off completely overnight), since heat pumps work most efficiently when providing a constant input of relatively low temperature rather than attempting to heat up quickly from a cold start (Energy Saving Trust, 2014).

Where energy costs vary through time, the algorithm can adapt the action of the heat pump to deliver the household's temperature requirements while minimizing energy costs. For example, it can undertake pre-warming when prices are lower so that set-point temperatures are achieved throughout higher pricing periods, while reducing the need to heat actively during these periods – thereby facilitating demand response. In the case of this trial, no limits were set to the level of pre-warming implemented by the controller even overnight. While the optimization algorithm takes into account increased heat losses due to higher internal temperatures and, therefore, is self-limiting, the decision to allow complete freedom has had important implications for thermal comfort.

Participant recruitment and group composition

The participating households were recruited on a convenience basis. The main group was recruited in partnership with a number of housing associations based in the south-west of England whose tenants were communicated to by letter and at public meetings, and opted to participate. Five additional homes that formed a beta-testing group, which were installed ahead of the main group, were individuals known to the research team. The treatment group for the demand-response experiments consisted of 26 homes that were part of the main group and the five beta-testing homes. All 31 homes were exposed to the same experimental control and tariff regime. Additionally, data are available from a control group of 45 homes that did not receive the HEMS and therefore were not exposed to demand control signals. This yielded a total of 76 participating homes.

All participants already had either air- or ground-source heat pumps installed, providing space heating via radiators. The homes were generally small (mean floor area of 55 m^2) one- or two-bedroom dwellings, similar to those illustrated in Figure 2. The homes typically have a European Union Energy Label rating of 'C' or 'D', according to our analysis of the available energy performance certificates (EPCs). They are generally of concrete or brick construction and, therefore, can be assumed to have a relatively large amount of thermal mass, although it has not been possible to measure this precisely.

Most of the participants were elderly retired households who tended to be at home during the day. This broad typology of homes, in rural areas without mains gas connections, are typical of the target market for heat pumps. However, the physical dwellings themselves and the occupancy patterns and lifestyles of the occupants, who are likely to be at home throughout the day, are not representative of the UK population as a whole. The implications of this are discussed further below.

Figure 2. Typical field trial dwelling.

The trial was approved by the UCL Research Ethics Committee (project ID 3760/003).

Trial design and tariff tests

Monitoring equipment was placed in participating homes during November–December 2014. The original design envisaged random assignment of participants to equal treatment and control groups, but internet connectivity and other issues meant that only a specific subsample of homes was suitable to use with the control system and therefore become the treatment group. The control systems were installed in these homes only, acknowledging the possible bias that this may introduce. However, as the occurrence of communications issues was stochastic, it is still useful to compare the treatment and control groups. Control systems were fitted in late January–early February 2015. Monitoring continued until April 2015. The project timeline is summarized in Figure 3.

For most of the data-gathering period, the treatment group operated in a 'flat-tariff' mode and, therefore, the controller aimed to minimize heat pump-energy consumption. The exception to this is a number of short periods, summarized in Table 1, where the homes were exposed to simulated time-of-use price signals which were downloaded to the control system. The tariffs are illustrated in Figure 4. The Economy 10 tariff represents a commercially available dual-price tariff designed to encourage bulk shifts in electricity demand, the Critical Peak tariff, on the other hand, was designed to stimulate a short-term demand reduction.

It is important to emphasize that the occupants were not in reality switched onto time-of-use tariffs during these periods so would not be expected to make other changes in their electricity-using activities. It is for this reason that the tariff-exposure periods were quite short, as otherwise there was a risk of bill impacts connected with operating the heat pumps to a different tariff
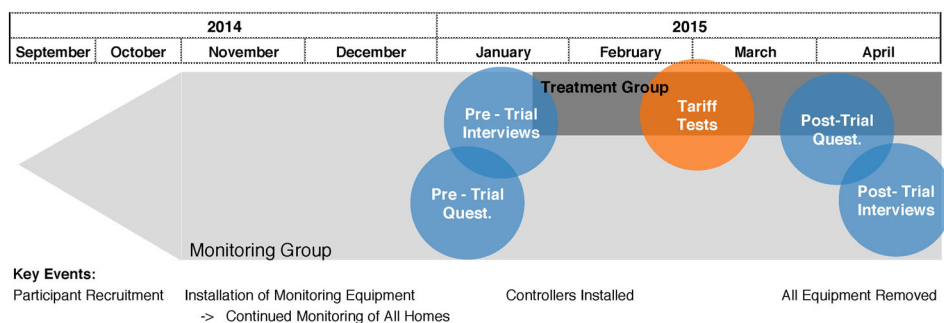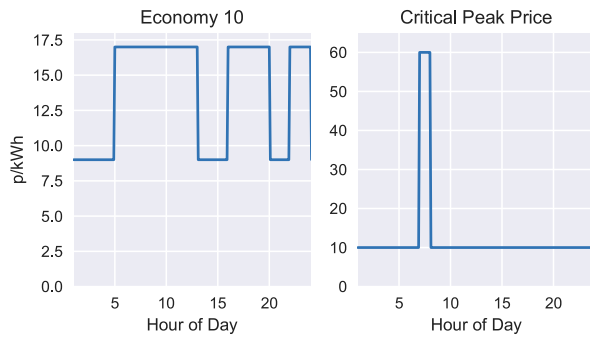

Figure 3. Summary diagram of the structure of the project.

Table 1. Tariff trial periods.

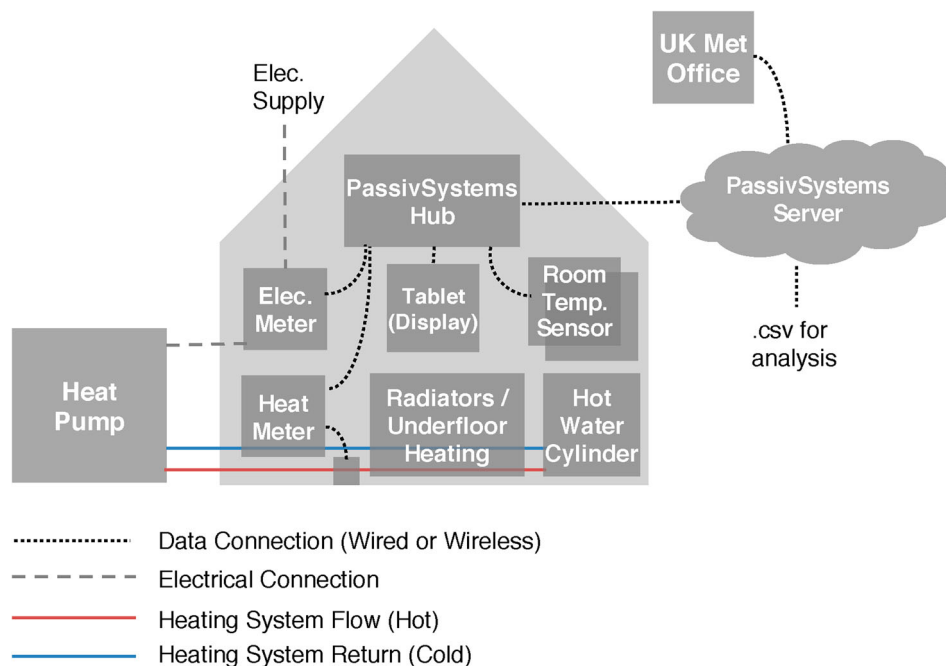| Experiment	Aim	Dates of the run
Economy 10	Demonstrate energy cost savings on a commercially available tariff	10–13 March 2015
Critical Peak (five pilot homes only)	Reduce demand during peak periods without prior knowledge	1–2 April 2015

Figure 4. Tariff structures.

structure from that which occupants were actually being billed on. However, participants were informed that one of the capabilities of the control system was to respond to demand for electricity on the grid.

Physical data gathering, cleaning and analysis

Installed equipment and data gathering

A number of sensors were deployed around the participating homes, as shown in Figure 5.

The data gathered during the trial were incomplete due to a number of technical issues, principally unreliable internet connections between the HEMS and the servers, but also due to individual sensor malfunctioning. This, coupled with the small sample size, meant it is difficult to draw statistically robust conclusions from the data. Nevertheless, it is possible to present some illustrative case studies and descriptive analysis that, in combination with the interview data, are illuminating. Table 2 summarizes the data points that are of relevance to this analysis.

Data cleaning

A number of data cleaning steps were performed:

- Homes with no heat pump energy consumption, zone 1 temperature or external temperature data were excluded.
- The target temperature data, which is a state signal, were processed to produce a 'square wave' time-series.
- Data gaps of more than 1 h were marked to allow them to be treated appropriately in the later analysis.
- Periods where the HEMS had been in operation were marked and the periods of each of the tariff experiments are also marked.

Data analysis

Where profiles are presented they have been derived using the following data-processing steps:

- 'Dummy' dates around the time of the installation of the controller in the treatment group were generated

Figure 5. Monitoring schematic.

Table 2. Data labels and descriptions.

Role	Description
Heat pump power consumption	Power consumption of the heat pump including immersion and inline heaters where these are present and metered. These measurements are taken at 1-min intervals
External temperature	External temperature recorded at a local weather station
User setpoint zone 1	User's target temperature in the main living space
Zone 1 temperature	Air temperature in the main living space (used for control)
Hall temperature	Air temperature in the hall
Bedroom temperature	Air temperature in the bedroom

to separate the control group data into 'pre' and 'post' periods. This ensures external weather conditions for both groups are near identical.

- The data were interpolated onto a 15-min grid by taking the mean over these time slots.
- All weekday days for the homes and date range of interest were grouped; weekend days were grouped separately.
- For each home the mean and upper and lower deciles for each of the 15-min time slots within the home's data set were calculated so both the mean and range can be understood. On completion of this stage, the processed data set contains a weekday and weekend profile of mean internal temperature (MIT) and a profile of the upper and lower deciles of internal temperatures and so on for each variable of interest.
- The final step is to calculate the mean of all the means and deciles of the upper and lower deciles for each time slot over all the relevant homes in the cohort. The outcome is a unified temperature or demand profile for each of the three trial periods.

The resulting profiles are presented as graphs for interpretation. In addition, a number of 'case studies' or plots of the raw data are used to illustrate points made throughout the discussion. In this case, selected portions of the '5 minutely' data are presented in their raw form with supporting annotations.

Social data collection and analysis

Surveys

A survey questionnaire was posted to all participants at the beginning of the trial before installation of the monitoring equipment, and a follow-up survey was posted to those participants who had received a control system in late March 2015, towards the end of the trial. Both collected basic information on age and number of occupants and occupancy patterns. The pre-trial questionnaire asked about current methods of heating control and satisfaction with current controls, while the post-trial questionnaire

asked about use of and satisfaction with the new control system. The questionnaires were also used to inform participants of various capabilities of the controller, one of which was the ability to respond automatically to time-of-use pricing. This was described as follows:

> It can also help reduce 'peaks' in electricity use on the national grid (these peaks make electricity more expensive and polluting for everyone). It can do this by heating more when demand for electricity is low, and less when demand is high – while always sticking to the temperatures you have set.

Interviews

Two rounds of interviews were held with selected sub-samples of participants. Telephone interviews were scheduled to take place before or shortly after installation of monitoring equipment (but before controller installation), and longer in-home household interviews towards the end of the trial once the controller had been in place for at least a month. As this paper is concerned with participant experiences of the new control system, the analysis focuses mainly on the post-trial interview data.

Participants were selected for a pre-trial interview based on a number of criteria, focusing on those who were assigned to receive the controller, and with a balance of those who indicated they would (hypothetically) choose to have the DSR function 'on' or 'off'. This yielded a total pre-trial interview sample of $n = 15$ participants who provided an interview. Post-trial interviews included the same households where possible. However, dropouts and changes in the group assignments meant this was only possible in four cases – with an additional four introduced who had not provided pre-trial interviews. Because other household members were encouraged to take part in the interviews where appropriate, the final interview participant sample was $n = 12$ (over a total of eight interviews).

Pre-trial telephone interviews focused on why participants decided to take part in the trial and their previous experience and views on DSR. Post-trial interviews were conducted in person in participants' homes. Questions focused on participants' general satisfaction with the controller; its ease of use; its ability to fit in with their schedule, comfort and spending requirements; and their views on the DSR function. All interviews were audio recorded and later transcribed verbatim. Qualitative content analysis of both the pre- and post-trial interview data was conducted by the author in NVivo 10 using codes generated from multiple passes of the data, and collecting these into themes.

Results and discussion

The results of the data gathering and analysis are structured around a number of central themes covering both

the socio-technical and physical aspects of deploying new technology, *i.e.* control system impacts (on temperature, comfort and energy use), demand response and controller usability. This section discusses those themes in turn. Where participants are referred to by name, pseudonyms are used.

Control system impacts

Temperature

Figures 6 and 7 show the main living space and main bedroom temperature profiles respectively for the control and treatment groups for periods before and after the installation of the controller. In both cases, the top charts show absolute temperatures in degrees Celsius pre-trial, the middle charts post-trial, and the lower charts compare temperature change throughout the day before and after the trial. The dashed lines indicate the mean; the shaded area covers the 10th–90th percentiles of the data recorded.

It is clear there was little change in the control group, while the control system maintained a much more even temperature profile in the treatment group. Although the overall mean temperature is practically the same, overnight temperatures are up to 1°C warmer than previously.

The temperature range, indicated by the grey shaded region, exhibits two notable changes in the treatment group. Firstly, the variation in the main living space temperature (which is the sensor used for control) is much reduced compared with the pre-intervention and control group data. This is likely a result of the harmonization of control strategies across the homes, previous approaches having varied from manual on/off to 24-h operation, and from the improved temperature targeting provided by the new controller. In the main bedroom data the overall level of variation is similar except that the upper decile has increased during the overnight period from approximately 22 to 24°C.

Overall, the data show little change in the MITs of the participating homes. Late night and daytime temperatures appeared to increase in the treatment group, which is consistent with the control system goal of achieving both more efficient operation of the heat pumps and effective demand response. The following section discusses the impact of these changes on occupant comfort.

Thermal comfort

Comfort was one key area addressed in the interviews. Of those interviewed, three households – Alan, Georgina, and Fionn and Francis – reported being broadly happy
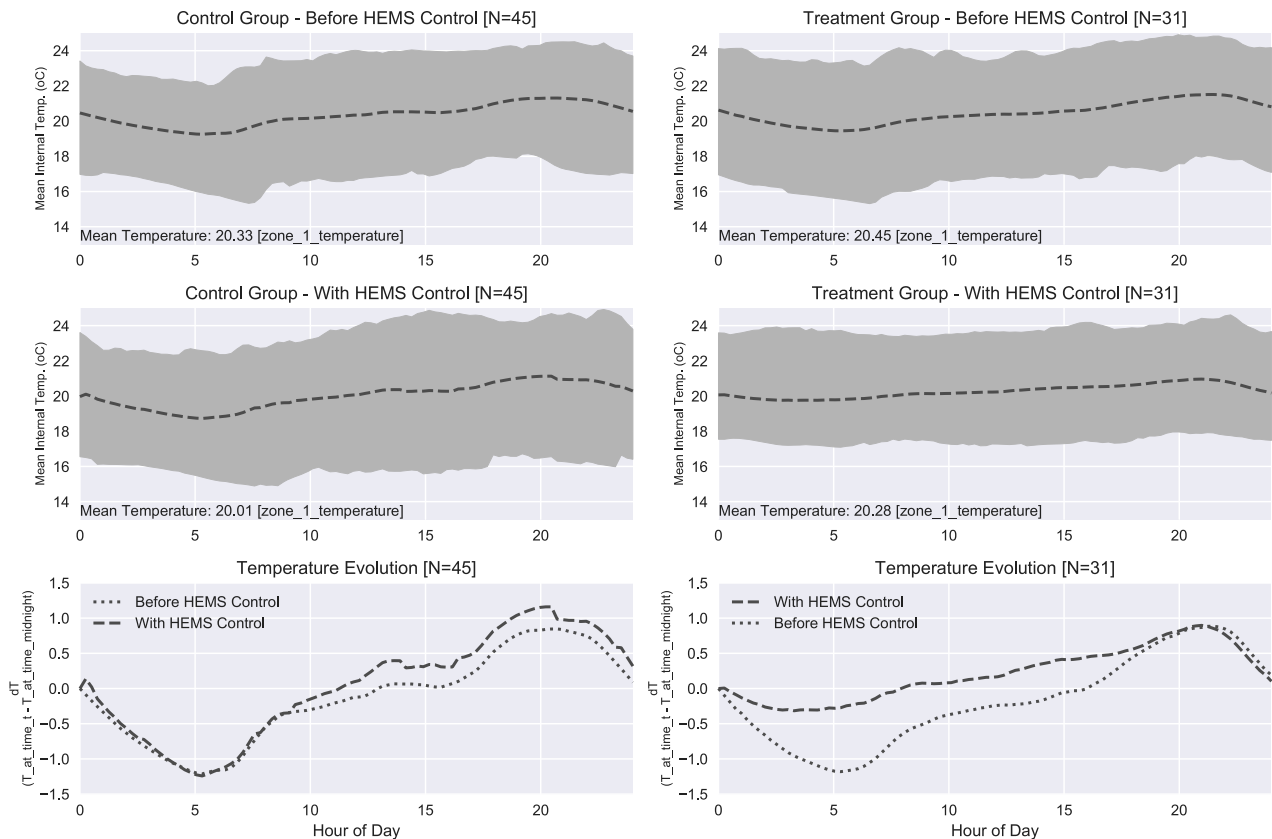

Figure 6. Impact of the home energy-management system (HEMS) on living space temperatures.
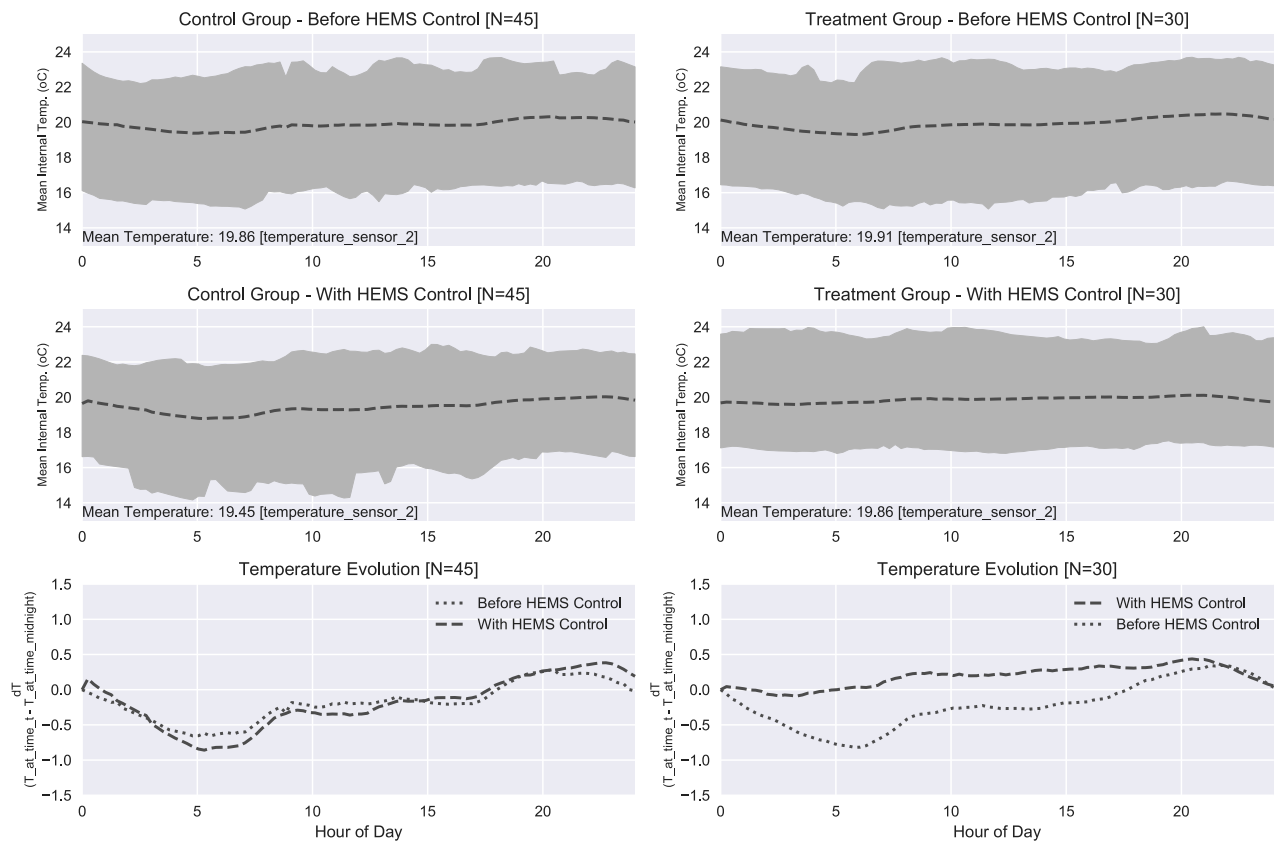
Figure 7. Impact of the home energy-management system (HEMS) on bedroom temperatures.

with the temperatures maintained by the new control system. The latter two households said they interacted very little with it via the tablet interface and were happy to let the controller operate with little interference from them. The remaining five households, however, reported problems with the temperatures they had experienced. The most significant of these appeared to be night-time overheating, for example:

> it was like being in the tropics for two nights … the butter melted in the butter dish on my kitchen table and there's no heat out there! (Christopher)

Two households had asked for the controller to be removed – mainly due to such temperature-regulation problems.

Overnight heating occurred for two reasons – to optimize the cost-efficiency of the heat pump and to facilitate DSR by pre-heating when (simulated) prices were lower overnight. Other participants reported experiencing it, even if it was not a problem for them personally, for example: 'it doesn't worry me too much because if it comes on, I think "oh, it's wasting electricity again," because I'm in bed' (Alan). As most participants knew that their controller was only set to provide heating during the day, this night-time activity was confusing and, to many (being unaware of how heat pumps are

most efficiently run), seemingly erroneous. Furthermore, participants who had air-source heat pumps reported an increase in fan activity overnight: 'and this blower out here. Should that one blow as much as it does overnight?' (David). The overheating and noise, combined with lack of feedback from the controller when they tried to turn down its operation (discussed in the section on 'usability and control'), led to a sense that they were not in control of their own heating system.

Many participants in the current trial had recent (mostly negative) experiences of night storage heaters, which often appears to have been somewhat mitigated by replacement with heat pumps (a finding also noted by Bell et al., 2015, during the Customer-Led Network Revolution trial). While new tariffs and optimization by HEMS devices can avoid some of the problems associated with legacy systems (*e.g.* by allowing more top-up heat during the day), unless additional storage is installed, they will be limited by the amount of pre-heating that can be achieved without undue impact on consumers' thermal comfort, as found here.

Energy-use patterns

Having found a relatively significant change in the temperature patterns in the treatment group we would expect

a similar change in the heat pump electricity demand patterns, and indeed this is the case as shown in Figure 8. In this case, the bottom graphs show the proportion of the total daily demand in each 15-min segment (to normalize the demand profiles). These profiles show a much slower ramping up of demand overnight as the controller attempts to optimize the heat pump operation trading-off increased heat loss caused by higher MITs and improved heat pump energy efficiency through smoother operation.

This change in the operation of the heat pump to a 'smoother' mode of operation is intended to improve the coefficient of performance (COP) of the heat pump. While the evening peak is reduced in the treatment group, the morning peak is seen to be similar to that in the control group, albeit with more gradual ramping up of temperature as mentioned above. We believe this is because the new control system is better achieving the morning target temperature than was previously the case in the treatment group. However, as discussed above, the night-time operation did not go unnoticed by the participants – which suggests there may be potential to reduce morning set points (to a level at which participants were previously satisfied), thereby saving energy.

Demand response

Tariff tests

In the course of the experimental period, a number of short tests, where a simulated time varying price was enforced, were carried out. When such a price signal is in operation, the controller attempts to operate the heat pump in a manner that minimizes predicted energy costs by using the thermal inertia of the building to store energy. The following profile graphs present the aggregate results of each of the tariff tests, where the control group is the same as previously discussed and the treatment group consists of the homes that received the tariff signal.

Figure 9 presents the living-area temperatures and heat pump electricity demand profiles for the homes during the Economy 10 test. The red shaded periods indicate the higher price periods, where we would expect the controller to minimize demand. The temperature evolution graph in particular illustrates preheating in advance of the 5 a.m. high price period which is repeated again before 4 p.m. (hour 16) and 10 p.m. (hour 22). The normalized electricity demand profiles show the demand peaks that result from this pre-heating both before the transition to a higher price and upon the transition to a cheaper price. These demand peaks, or 'crowding', are an issue seen throughout the analysis. In this case,
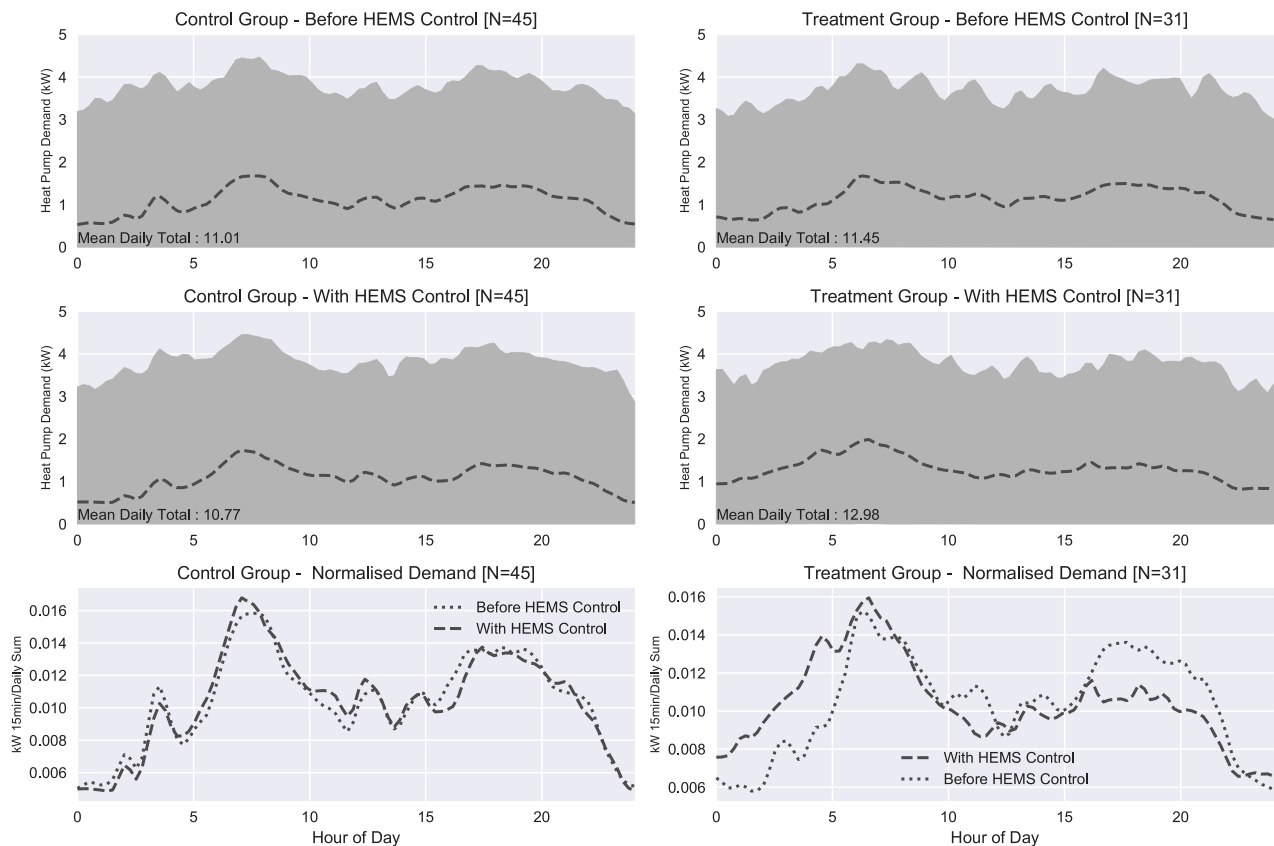

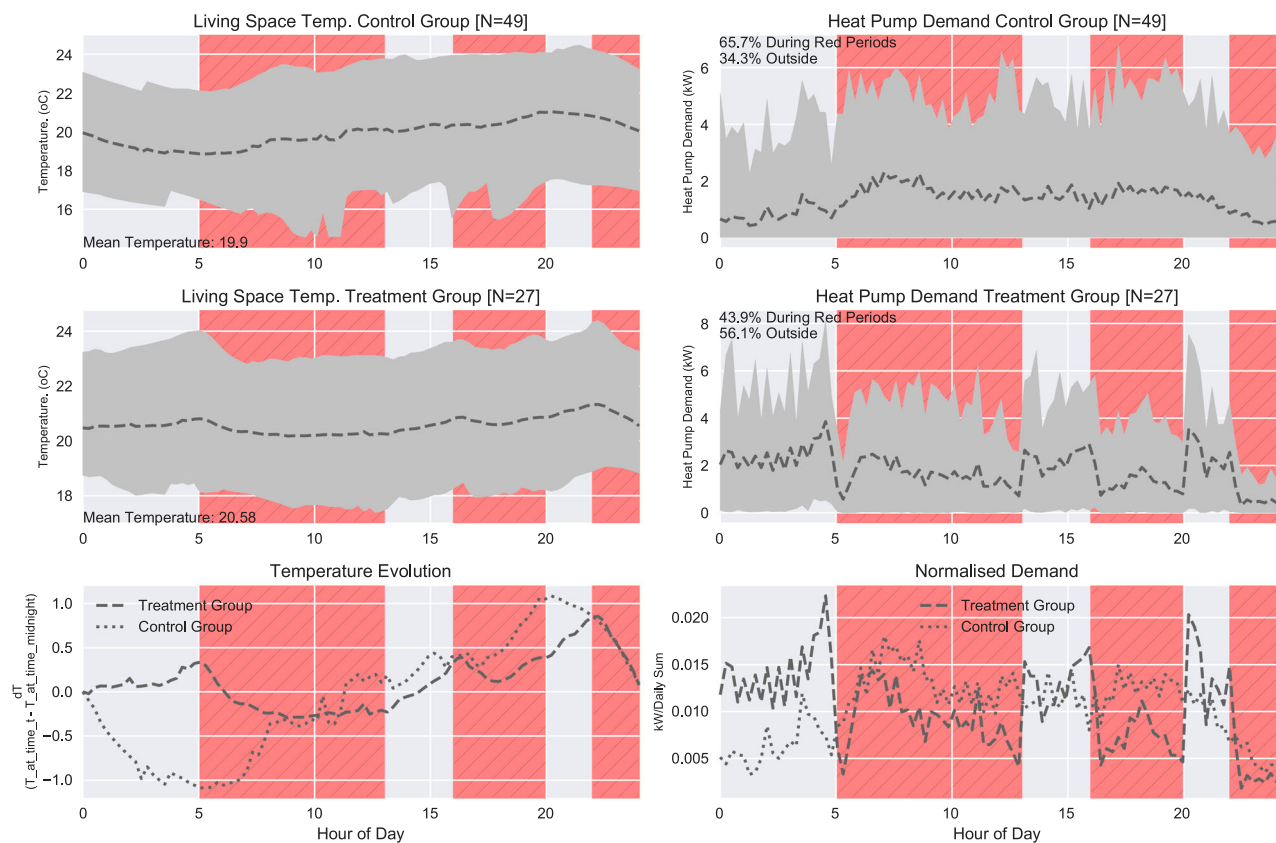**Figure 8.** Impact of the home energy-management system (HEMS) on heat pump electricity-demand patterns.

Figure 9. Economy 10 profiles. Red shaded regions indicate the higher price periods.

we also observe reasonable levels of demand during the high-price periods, although lower than in the control group. There are various reasons for this, including occupant intervention, which are discussed when we examine the case study data.

The Critical Peak Price (CPP) tariff was tested on a smaller population of the field trial population consisting of just five homes. In this case, the tariff was sent to the homes minutes before the high price period came into force, so there is little evidence of a demand spike before the tariff transition. During the high price period there is a dramatic reduction in demand with little impact on the temperature profile (Figure 10). It seems likely that this sort of short-term adjustment of temperature would be less impactful on consumers than that observed with the Economy 10 tariff.

Case studies

The temperature and energy analysis so far has considered the groups in aggregate. However, to understand better specific issues highlighted in the qualitative research, it is useful to focus on a number of case studies of individual homes, which were selected for their clear illustration of these issues. Table 3 gives an overview of annotations used in the graphs. While it would be inappropriate to

make statistical inferences from these case study findings to a wider population, they serve to highlight the sorts of issues that could arise and therefore merit further investigation and (potentially) management.

Case study 1 is an example of demand shifting in action and working relatively well. Figure 11 shows the internal temperatures, target temperatures and heat pump power demand during the Economy 10 tariff test.

During the overnight low-price period, the heat pump runs at high output increasing the internal temperature in advance of the higher price (denoted by red shading). There are clear increases in the living space temperature (zone_1_temperature) as the system charges up the home (the points marked 'charging'). During the expensive periods, the heat pump operates at a low level, keeping the temperature topped up (the points marked 'top up'), except where the set point is manually increased (point OR) and living room temperature therefore also increases. In this case, the bedroom temperature (temperature_sensor_2) is very stable, possibly due to the physical characteristics of the home or the occupants' use of controls, such as thermostatic radiator valves (TRVs). This is confirmed by the occupant in interview:

> I set those [TRVs] when I came in, I set it at what temperature I wanted, the bedroom for instance, I don't have that terribly warm. (Georgina)
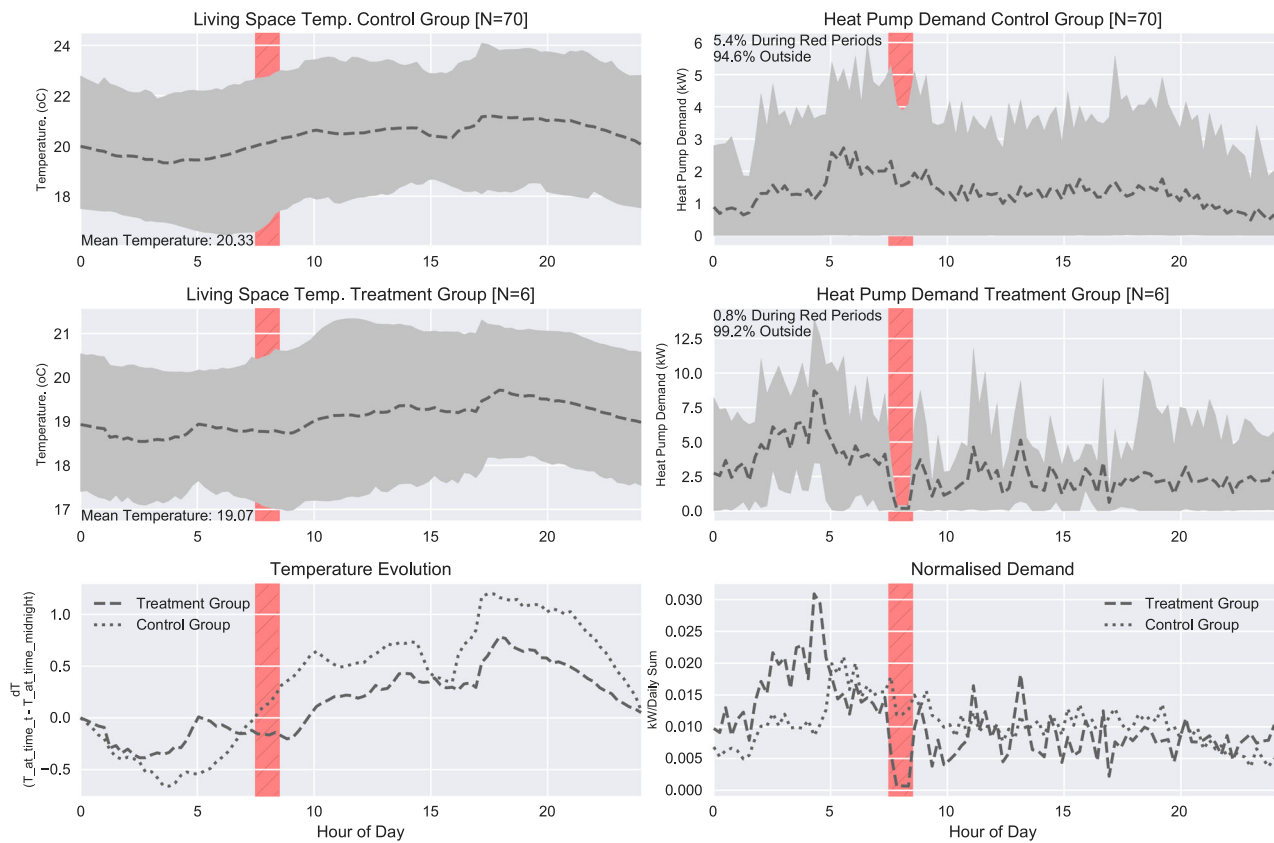
Figure 10. Critical Peak price profiles. Red shaded regions indicate the higher price periods.

All three of the participating households who did not complain of overheating explicitly reported turning radiators down in bedrooms, or opening windows, and in one case (although likely in others): 'clos[ing] the bedroom door, so this radiator's not working extra hard to warm the bedroom' (Francis).

The data for case study 2, presented in Figure 12, present a more complex picture. In this case, the bedroom temperature exceeds that in the living space, *e.g.* at point 'high temperature'. During the following day, the occupant makes multiple changes to their target temperature, at 'over-ride', first decreasing then gradually increasing the target temperature through the day. This causes the heat pump to run during the expensive price periods. This is a good example of the conflict between encouraging users to update their schedules regularly in order to avoid unnecessary heating and save money and the need to be able to predict temperature demands in order to respond to time-varying prices.

In Figure 13, showing case study 3, bedroom temperatures (temperature_sensor_2) can be seen to exceed the main living space temperatures throughout the demand shifting. In this instance, set points are also relatively high at times, with quite a high level of occupant interaction (denoted by 'over-ride'), boosting the target temperature to 24°C at one point. The occupants of this house reported overheating in the interview along with some technical problems and difficulty using the controller (see the section on 'usability and control' below), and requested that the controller be removed. Examining the 'power' graph, the interventions made by the occupants have had a detrimental effect on the HEMS' ability to shift demand. During the period marked 'charging', the heat pump runs continuously in an attempt to store energy in advance of the high tariff period;

Table 3. Key to case study annotations.

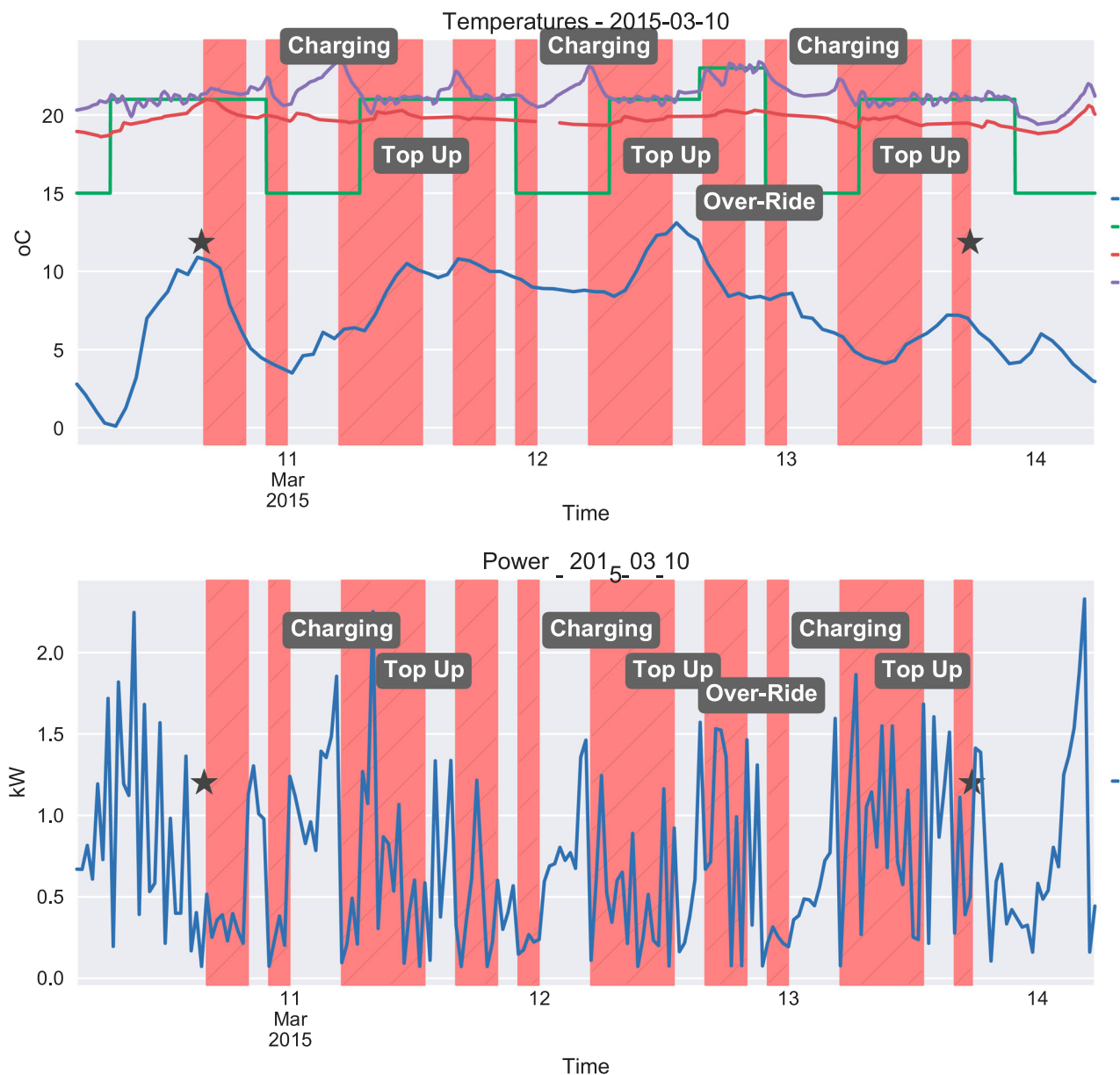|	
Charging	Indicates areas where there is evidence of the HEMS storing energy in advance of a high price period.
Top up	Indicates points where there is evidence of the HEMS having to top up the temperature in order to maintain the set point temperature.
Override	Indicates instances where the household occupant has used the controller to make an 'in the moment' change to the set point temperature.
High temperatures	Indicates periods where the internal temperatures were high/excessive and may have caused discomfort to the occupants.
Window open	Indicates rapid decline in internal temperature, possibly a result of window opening by the occupants.
High set point	Indicates points where high set-point temperatures are apparent

Figure 11. Case study 1 temperature and power profiles.

however, shortly afterwards, at 'over-ride', the set point is increased forcing the heat pump to run during the high-tariff period.

These brief case studies highlight some of the individual idiosyncrasies that might be experienced in deploying DSR technology in the real world, and the sort of issues that might prevent these systems from achieving their full potential. There is evidence that occupants' pre-existing heating routines (concerning their operation of the heating system, TRVs etc., but also use of doors and windows) will influence how acceptable the kind of intervention tested here will be. The ramifications of this are discussed in the concluding section, but before that we briefly consider questions of usability and also the specific context of the trial.

Usability and control

The new control interface included with the HEMS was designed to be more user friendly than the typical control interfaces provided with heat pumps. The ability of users to understand and effectively express their comfort requirements and control their environment via the controller is expected to be vital for successful (and acceptable) demand shifting. Firstly, it was noted that almost all participants reported experiencing some kind of technical problem with the controller during the trial. Communications (i.e. between the tablet interface and the hub, or the hub and the remote servers) was a big challenge for the project, and indeed it had led to the smaller-than-anticipated number of households in the trial
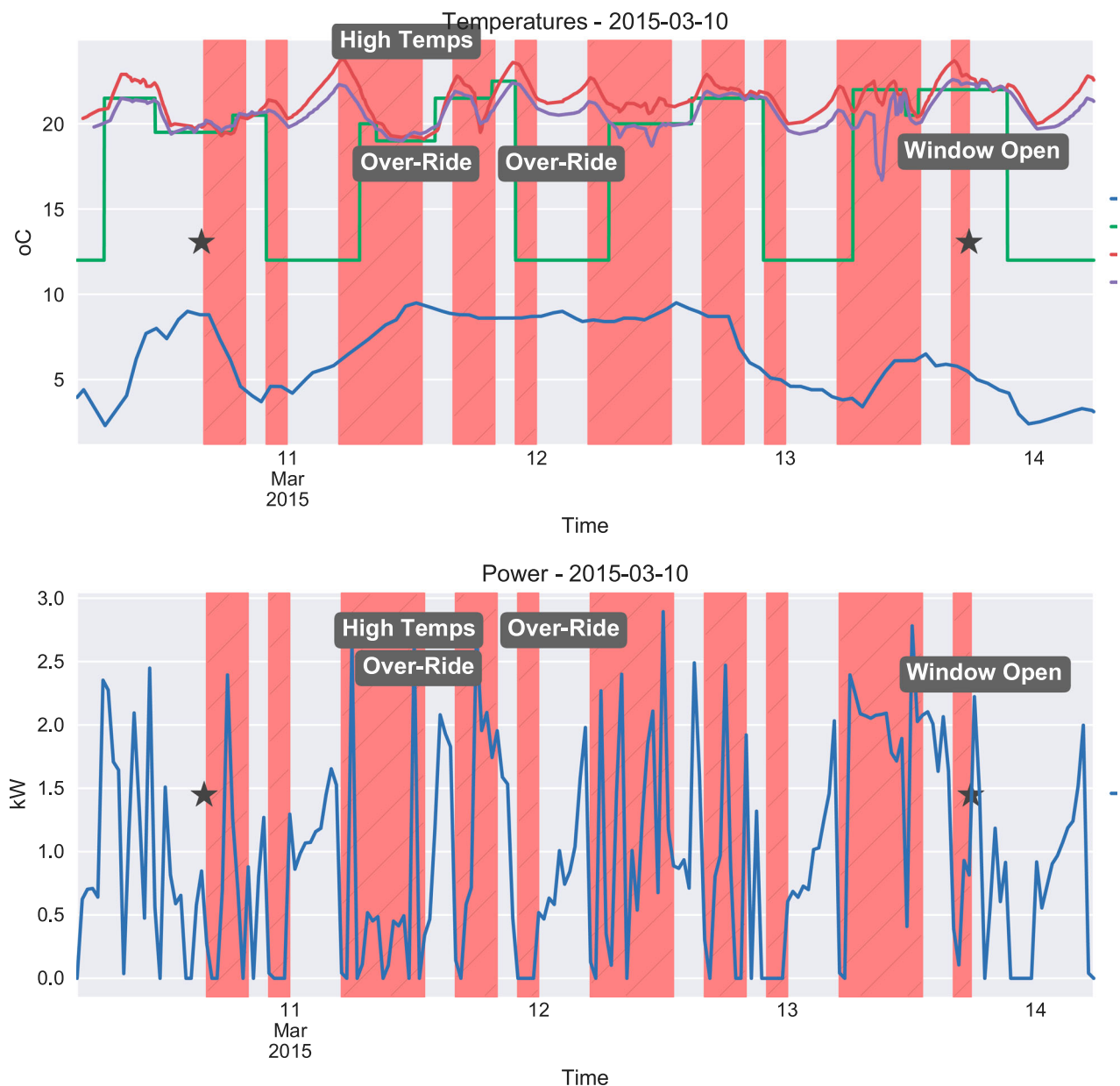
Figure 12. Case study 2 temperature and power profiles.

receiving the controller. Certain system hardware components brought in specifically for the trial also did not perform to the expected standard. In some cases, participants reported technical problems, but no evidence was found of them on inspection during the interview. On observing the participants using the controller, it seemed likely they were not using it as the designers intended. For example, some participants were fully shutting the tablet down and restarting it each time they wanted to use it, rather than just letting it stay in 'sleep' mode. Whether technical issues are real or a result of misuse, the result was that this negatively affected these participants' overall experience of the new control system and, apparently, of its DSR function.

One key objective was that the new controller be easy to use. Participants' views on whether this objective were accomplished were mixed. The main factor tended to be whether or not participants considered themselves to be 'tech savvy'. For example, Alan, a former engineer, had little problem learning how to use it: 'Yeah [it was easy to use] because if you look in there, you'll find that I've got loads of computers and stuff there.' At the other end of the scale, various participants reported either lack of experience with, or antipathy towards, information and communications technology (ICT) such as computers and smartphones: 'I'm a bit of a technophobe really' (Barbara). In such cases, participants reported
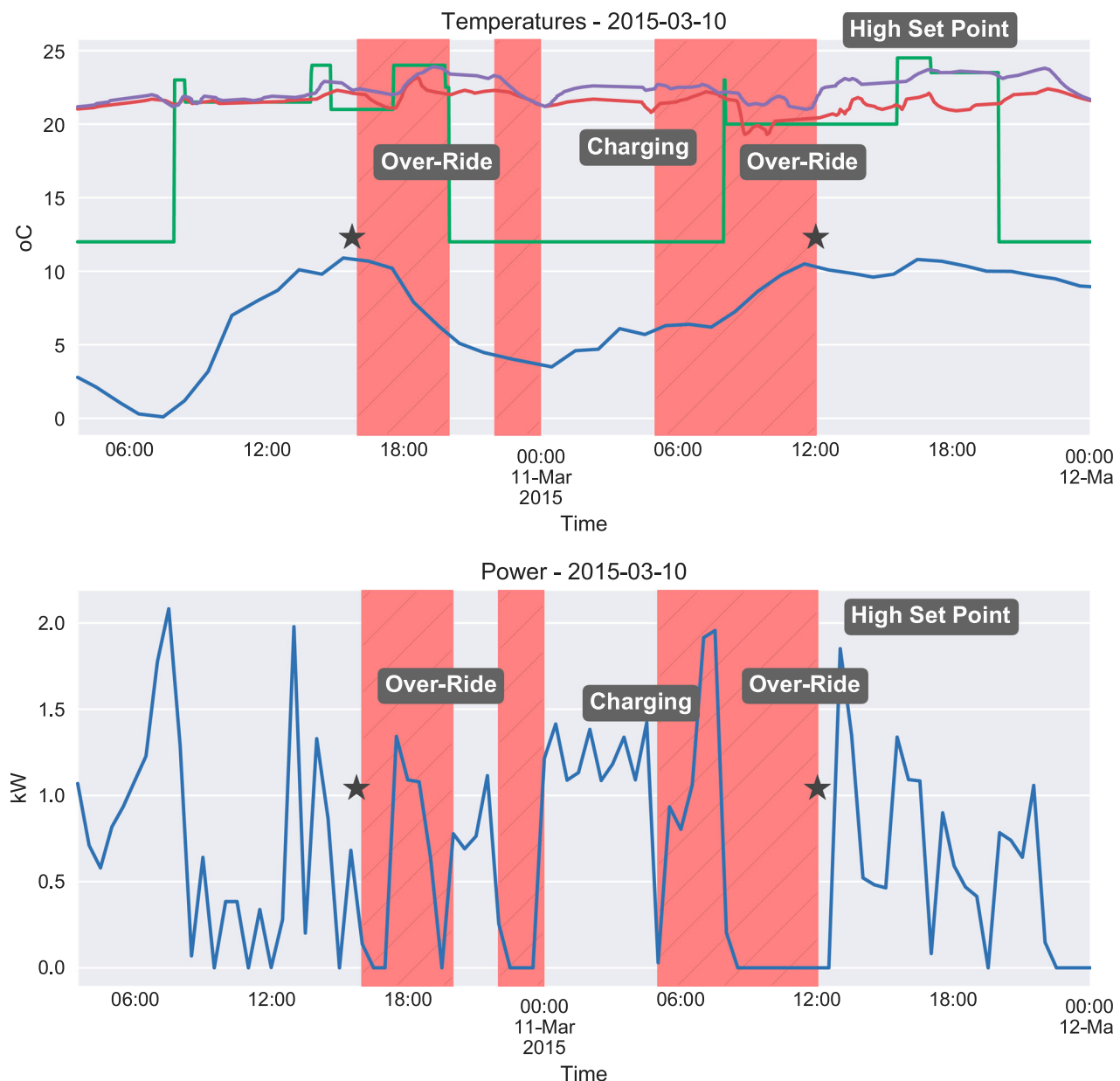
Figure 13. Case study 3 temperature and power profiles.

difficulty using the controller, or just a general feeling that it was not suitable for them:

> For people like you, who can understand it, all this gadget stuff, fair enough, it's easy, but not for. … I'm 74 and I don't want anything where I've got to press this and press that. (Christopher)

One common source of confusion (reported by four of the interview households) was that when participants pressed the 'minus' button to reduce the thermostat set point, they expected to see the central number showing the current internal temperature reduce. However, the combination of heat pump and building fabric has a slow thermal response, and with no cooling provided,

the internal temperature would only fall slowly (or not at all if other gains were causing the house to heat up). When the outcome of actions is unclear, there appears to be lack of a connection between actions and outcomes (or contingency), diminishing the sense of control which was one of the main aims of the new control interface.

All the participants were asked for their view on the system being externally monitored by the HEMS provider. This was widely accepted, and indeed participants sometimes welcomed the fact that problems could be diagnosed remotely: 'It's fine. If it's gonna improve the heating and hot water system for us, I don't mind that at all' (Francis). There was, however, some confusion as to whether the HEMS provider was only monitoring

the system or were actually able to control it remotely: 'They're like Big Brother, keeping an eye on you. They seem to have more control, maybe, than I have, I don't know' (Alan). Participants also reported that the HEMS provider's monitoring sometimes showed results that was at odds with their own experience:

> … I said, 'and I haven't got any heating.' He [the installer] said, 'Well, this is showing that your heating is working.' That didn't give me a lot of faith, or encouragement. (Barbara)

Reliability is naturally (and must continue to be) a key concern of product developers and manufacturers – recognizing, however, that combining innovative controls with heat pump technology that is not yet fully mature in the UK (*e.g.* concerning installation; Energy Saving Trust, 2010) is likely to mean that technical issues of the kind experienced here remain a reality for some time. For future systems to meet their full potential, considerable further development and testing will be required.

Contextual considerations

It is important to emphasize again the context in which this trial was conducted. All the participants were social housing tenants living in the south-west of England. Many of them (and all those who participated in the post-trial interviews) were older than 65 years and lived in dedicated retirement properties. It is therefore useful to consider two questions. To the extent that the participants tested here are representative of people with similar characteristics, how important is this group in the context of DSR? To what extent might the findings discussed here be relevant in the wider context of Britain?

According to diffusion of innovations theory (Rogers, 2003), initiatives such as automated DSR would be expected to be taken up first by innovators and early adopters. Being a largely technological innovation, considerations such as an interest in new technology might be expected to feature in whether someone falls into one of these brackets. The post-trial participants often emphasized their lack of interest in technology, and compared with younger participants in the pre-trial interviews, showed little interest in features such as the smartphone app. This is consistent with national statistics on use of ICT. For example, just 25% of people aged over 55 years owned a smartphone in 2014 compared with 88% of people aged 16–24 years (Ofcom, 2014). The key point, therefore, is the importance of providing a user interface (UI) appropriate for the target audience, whether that be via a tablet as tested here, a mobile phone or a re-imagining of more traditional timer and thermostat interfaces.

Another potentially unusual characteristic of the study participants is that, as residents of retirement properties, they may be more-than-usually accustomed to the idea of external parties having involvement in their home life. For example, wardens based nearby would have keys to homes allowing them access in case of emergency – a situation that would not be the case for people in most other forms of accommodation. Among other things, this might be expected to increase participants' willingness to accept external monitoring and control of their heating systems as the interview results imply.

Nevertheless, there are also reasons to believe that demographics such as those involved in the trial might well be at the vanguard of exposure to innovative automated DSR. A decision was taken to work with social landlords because they were likely to find high heat pump penetration amongst their tenants. Housing associations are in a position to install large numbers of both heat pumps and, if they choose, smart thermostats with the potential for automated DSR of the kind tested in this project. This is all the more likely in rural areas away from the gas grid such as that involved in this trial. Such areas might also be expected to be more prone to network constraints and faults, *e.g.* due to extreme weather, making the local need for effective DSR more pressing. Finally, older people are more likely on average to be at home during the day (McKenna, Broome, & Liddle, 2007), requiring heating but therefore also using electricity which, in theory, should provide flexibility to the grid. It is therefore not unreasonable to expect that demographic groups such as that represented in this study would be of significant interest for DSR operators. More generally, there is no reason to believe that problems such as technical issues, night-time overheating and noise would be experienced as less problematic by other groups than the one focused on here.

Conclusions

This paper has presented the results of a trial of a new control system that aims to optimize heat pump operation, with or without time-varying tariffs.

The analyses of the measured data in 31 homes showed that the HEMS delivered a more even internal temperature in their efforts to maximize the COP of the heat pumps by slightly increasing late-night and daytime temperatures. The time-of-use tariff experiments showed mixed results. The CPP test resulted in a marked reduction of demand with no

evidence of 'crowding' before the price increase. The Economy 10 test was less successful; consumption during high price periods was greater than expected and new peaks in demand were created in advance of price increases. Analysis of the case study data has indicated that this was partly due to participant intervention and partly due to the physical nature of the dwelling and heating systems.

These results highlight the challenge involved in delivering load shifting over long durations while generally respecting consumer comfort. No dedicated heat storage was present in the trial homes, which may be expected to be a common situation in the UK if the current trend of hot water tank removal continues. This will severely limit the level of demand flexibility available from heat pumps. During the trial, pre-heating in advance of high price periods led to overheating and noise which was unacceptable to participants; however, short-term demand reductions could be delivered with minimal impact on internal temperatures. These issues may be resolved by taking into account the thermal limits of occupants, which may differ between the daytime and overnight, within control algorithms; however, this will decrease the volume of energy that can be stored. These limitations in demand flexibility are also likely to limit the economic benefit available to the occupants. Better use of zoning to limit overnight pre-heating to living areas may help to overcome night-time comfort limits somewhat, although further research is required to understand the trade-offs. Similarly, noise problems could be tacked by ensuring heat pump fans are positioned away from bedroom windows.

Aspects of the ease of use of the control system were shown to be important in determining participants' attitudes towards using it. The interview and questionnaire results highlighted aspects of the UI design that made it hard for participants to connect their actions with a tangible outcome. This meant that participants did not consider themselves to have a viable override opportunity when, for example, high temperatures were experienced as a result of pre-warming. This serves to emphasize the importance of the users' perceptions of being in control – this is likely to be an important factor in acceptance of automated DSR (*e.g.* Butler, Parkhill, & Pidgeon, 2013). It may be possible to address this issue with improved UI design.

Finally, it is important to emphasize that even though automated DSR systems may be some way from the commercial mainstream in Britain, the conditions under which they will require to work effectively are already being created, *e.g.* in the way that heating systems are installed and buildings constructed and retrofitted to allow for actions such as pre-heating. Part of ensuring the acceptability of DSR will be in anticipating and further researching the sort of problems raised by this trial and acting now to avoid them.

Disclosure statement

No potential conflict of interest was reported by the authors.

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