# Load shifting with smart home heating controls: satisfying thermal comfort preferences

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## Keywords

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## Abstract

This paper investigates how UK households react to changes in daily heating patterns from a hybrid heat pump and the altered diurnal temperature profiles, which result from these new heating patterns.

In the UK over 80 % of homes are heated by gas boiler heating water circulating through radiators. Most emissions reduction scenarios include a major shift to electric heat pumps. This would change home heating dynamics significantly because UK households are habituated to significant temperature fluctuations over the day as gas boilers are typically only operated in the morning and evening. Electric heat pumps run for longer at lower outputs than gas boilers and are likely to require demand management to shift times of heating operation away from electricity network peaks. Consequently the patterns of both heat delivery and the resultant room temperatures are likely to change, flattening the diurnal temperature profiles currently found in UK homes.

Results are presented from a UK trial in which conventional gas boilers were replaced by a "hybrid" combination of electric heat pump and gas boiler, operated by smart heating controllers. Setpoint and actual temperature data from heating controllers in 71 homes were analysed and compared with data from conventional heating controllers in 3,579 homes. Interviews with 11 households explored residents' reactions to the changed heat delivery patterns from the heat pump.

Interview responses indicated that residents' temperature requirements are not simply linked to patterns of occupancy but also to the timing of practices taking place in the home, such as childcare. Analysis of setpoint data showed temperature settings were adjusted manually upwards in the evening in a significant proportion of trial homes, indicating a change in temperature requirements at this point in the day.

The implications for home heating control and demand management are discussed, in particular the need to satisfy varying temperature requirements at different times of day.

## Introduction

### HEAT PUMPS AND HYBRID HEAT PUMPS IN A UK HEATING TRANSITION

Direct emissions from fossil fuels for domestic heating made up 13 % of UK total emissions of greenhouse gases in 2015 (CCC, 2016). There is increasing attention on decarbonising heating as an essential step to meet UK emissions reductions targets (CCC, 2018, 2016; DECC, 2012; Wilson et al., 2018). Currently the predominant fuel is gas, with around 90 % of homes having central heating with a fossil fuel boiler, the vast majority of these supplied by natural gas (National Statistics, 2018). Proposed pathways to decarbonisation involve varying amounts of electrification of heating and decarbonisation of the gas grid (switching to biogas, synthetic gas or hydrogen). A common feature of many decarbonisation scenarios is that electric heat pumps play a significant role (Leveque and Robertson, 2014).

UK households typically operate heating only in the morning and the evening and there are currently peaks in gas demand for heating at these points in the day. If, following electrification, heat pumps are operated in a similar pattern to boilers; these peaks will transfer to the electricity network. This presents a significant challenge for the electricity system, which

has to match supply to demand on a second by second basis (unlike the natural gas network for which fluctuating pressures in the transmission pipework allow smoothing of demand) (Wilson et al., 2018). Demand management to reduce peaks on the network involves operating the electric heating earlier than it would otherwise have operated.

Electric heat pumps (both air source and ground source) have different output characteristics to gas boilers. They run most efficiently when delivering water at low temperatures and are sized with lower capacities than boilers (Dunbabin et al 2013). Many heat pumps are thus configured to run continuously overnight or for an extended "pre-heating" period, which contrasts with the situation today when many households simply manually start a fast-acting boiler when they wake up (Rathouse and Young, 2004).

Hybrid heat pump systems combine many of the advantages of both boiler and heat pump. The hybrid heat pumps considered in this paper consist of a heat pump in parallel with a gas boiler, operated with a common control system, The gas boiler allows rapid response to instantaneous requests for heat and the hybrid system can utilise the flexibility and energy storage capacity of the gas network during periods of high demand for heat or power (such as cold weather periods and midweek evenings). Hybrid systems can be retrofitted around existing heating systems, retaining the existing radiators and also the existing boiler (CCC, 2018; Element Energy, 2017).

Modelling for the Committee on Climate Change suggests that hybrid heat pumps could play a significant role in a heating transition. The CCC report also suggests that hybrid heat pumps could be a component of a future system in which the natural gas distribution system is switched over to hydrogen (CCC 2018). Hybrid heat pump systems offer two ways to manage electricity network peaks: switching fuel between electricity and gas and moving the electricity demand to an earlier time. In order to combine the flexibility needed to manage electricity network peaks with meeting the heating needs of individual households, a sophisticated control system is required. A smart heating controller provides the setpoint temperatures by operating either the heat pump or the boiler, selecting the heat source with lowest cost.

#### OVERVIEW OF THE RESEARCH

The previous section described the role of smart heating control in balancing the needs of households for heating at particular times with the electricity network need for flexible running of hybrid heat pumps in order to manage demand peaks. For households accustomed to a gas boiler, changing to a hybrid heat pump (or to a stand-alone heat pump) will mean they experience unfamiliar operating patterns. There will be pre-heating ahead of times when warmth has been requested, both to warm the house using lower cost electricity and to avoid periods of peak electricity demand. This means there is a difference between the times when the heat source is operating and the time when the occupants have specified they want the house to be warm. Residents must adjust from choosing when they want the heating to run, to choosing when they want to be warm and allowing the control algorithms to operate the heat sources to deliver this warmth. It is important to understand household reactions to this unfamiliar situation since, if new modes of operation do not meet residents' needs (or are hard to understand), this could lead to resistance to new types of heating.

A UK hybrid heat pump trial provided an opportunity to investigate households' reactions to a change from conventional boiler heating to a heating system with pre-heating ahead of the times occupants have requested warmth. Changed patterns of heating operation lead to changes in the daily temperature profile experienced by residents and this paper describes reactions to this different thermal experience. The study also investigates the reasons why households request particular temperatures at particular times, in order to understand the patterns of warmth they want from their heating system. This can inform control system design, by checking that design assumptions about what people want from their heating actually match the needs of the households involved.

Data from trial participants' heating controllers was analysed to investigate the pattern of temperatures experienced in the trial homes, and the setpoint temperatures that these households were requesting. Interviews with some of the trial participants explored the households' reactions to the new thermal experience. The interviews investigated whether households had varying temperature preferences at different times of day, and the reasons given for these preferences. This combination of quantitative and qualitative data provides novel information about how and why heating temperature setpoints vary at different times of day.

Data from this trial was compared with a large database from controllers operating conventional heating. This allowed assessment of the different thermal experiences of the two groups, and comparison of the patterns of temperature setpoints.

## Background to the investigation

#### THE FREEDOM HYBRID HEAT PUMP TRIAL

The Freedom trial of hybrid heat pumps took place in 75 homes in Wales during the 2017–18 heating season (the trial included a total of 40 social homes and 35 private homes). The hybrid system combined an air source heat pump (rated at either 5 kW or 8 kW) with a "combi" gas boiler. All the homes had previously had conventional gas boilers. The project aimed to investigate "the network, consumer and broader energy system implications of high volume deployments of hybrid heating systems" (Freedom Project, 2018).

Each home had a PassivSystems controller which ran an algorithm to decide when to operate each heat source, based on predictive demand control using a dynamically controlled flow temperature. The residents did not control which heat source was chosen or when it operated. The key input to the algorithm was an electricity to gas price ratio. The control strategy was to run the hybrid heating system at least cost to the householder. Demand was shifted to take advantage of the lowest prices while "ensuring that the comfort requirements of the occupants are met" (Freedom project, 2018). The implicit definition of comfort is that the air temperature at the thermostat reaches the temperature setpoint at all times residents have specified they want the house to be warm.

The Freedom project partners carried out a number of planned interventions during the trial to investigate the impact of different electricity pricing patterns on the aggregated gas

and electricity demand across all the homes in the trial. Various patterns of tariffs were simulated by pushing different fuel cost ratios to the controllers. This meant that residents were exposed to a variety of different heat pump and boiler operating patterns.

A major change experienced by the trial participants was the difference between the times when the heat source was operating and the time when the residents have specified they want to be warm. Whichever heat source was selected, there was a period of pre-heating before the scheduled start of the "IN" period to bring the house up to the specified temperature at the beginning of the period. The pre-heating was prolonged if the algorithm was also shifting demand earlier to avoid times of peak electricity demand.

Data was available from controllers in 71 homes in the trial and was cleaned by removing any days with no available internal temperature data and days when faults / lack of communication were indicated. Data for whole days was removed since the day was the key unit of analysis, for example in investigating maximum and minimum temperatures in the day and number of setpoint changes in the day. A total of 2,096 days remained following cleaning of the data from 71 homes for weekdays in the 8 weeks starting on 8 January 2018.

#### HEATING CONTROLLER DESCRIPTION

The smart heating controllers for both samples were supplied by PassivSystems Ltd. The user sets up an 'occupancy schedule', entering the times each day they will be IN, OUT and ASLEEP and what they would like the temperature (at the thermostat) to be in each of these periods. These terms are capitalised throughout the paper to indicate the controller 'occupancy' states; these may or may not coincide with the actual times that residents are at home, out, or asleep. Different schedules can be set up for different days of the week.

With PassivSystems controller preferred temperatures setpoints are set in two ways:

- In the pre-programmed schedule – the time and the temperature for the IN and other periods can be changed in the mobile phone app or on a website.
- Manually via a mobile phone app or directly on a thermostat to give a "right now" change in setpoint.

The temperature measured at the thermostat (which PassivSystems recommend should be located in the living room) is recorded every time it changes by 0.2 °C. A measurement of outdoor dry-bulb air temperature at the nearest Met Office weather station is recorded every hour and this is used as the external temperature for the control algorithm, which builds a model of how quickly the building heats up in different weather conditions.

#### HOUSEHOLD INTERVIEWS

Households participating in the Freedom trial were asked to volunteer to speak to the researcher. The trialists who responded positively to this request were contacted to arrange an interview in their home. The lead author carried out interviews with 12 households participating in the trial, seven of these before or during the installation and five who already had the system installed. Follow up interviews were held by telephone to ask about reactions once the new system was running with six households out of the seven who were visited before installation. In summary, information was gathered about the home, the household and the heating system before the trial for a total of twelve households, and during the trial reactions to the new heating system was collected from 11 of these homes. Four of the interviews were in social housing, the remainder in privately owned homes. The interviewees are referred to by pseudonyms in this paper.

Semi-structured interviews were held using an interview guide, which drew on Gram-Hanssen's (2010) framework of "practice elements". This framework has been used in analysis by a number of other energy researchers e.g. Behar (2016), Morgenstern (2016), Foulds et al. (2013). The practice theory framework also inspired questions on the links between heating schedules and different practices carried out in the home. Additional questions were developed based on the literature on Adaptive Thermal Comfort (de Dear and Brager, 1998; Nicol et al., 2012), which points out that residents have a range of options (such as changing clothing) to adapt their thermal conditions alongside operating heating controls.

#### COMPARISON WITH CONVENTIONALLY HEATED HOMES

A substantial database from PassivSystems controllers in homes with conventional gas or oil boilers was used to compare the setpoints requested and thermal conditions obtained with those in the hybrid trial homes. This sample consisted of 3,579 homes distributed across the whole of the UK. The data was cleaned by removing any days with no indoor temperature data, 7 % of the data (for 3,579 homes over 40 weekdays in January and February 2016) was removed.

The conventional heating data are from this separate set of homes, which may not have the same distribution of physical characteristics as those in the hybrid heat pump trials. Both samples include a wide range of homes of different sizes and ages. The data for conventionally heated homes displays a similar temperature profile to that reported elsewhere for a nationally representative sample (Huebner et al 2015).

The analysis for both samples involved processing data showing the temperature in the home (measured at the thermostat), the temperature setpoint chosen by the user and the outside temperature at a local weather station. Because it includes data for setpoints, the PassivSystems data provides an opportunity to investigate what temperatures residents are requesting, and whether these vary at different times of day. As far as the authors are aware, this is the only analysis of actual recorded setpoints (rather than setpoints inferred from actual temperature measurements or reported by the residents) in the UK apart from the work by Morton (2016). Very few investigations of setpoint levels in other countries have been published. These include Huchuk et al. (2018) who analysed setpoint data from North American homes and Fabi et al (2013) who investigated thermostatic radiator valves (TRV) settings in 13 Danish dwellings.

## Temperature variation during the course of the day

Analysis of temperature data from the conventional heating and hybrid heat pump samples allowed comparison of the patterns of temperature variations in the two sets of homes.

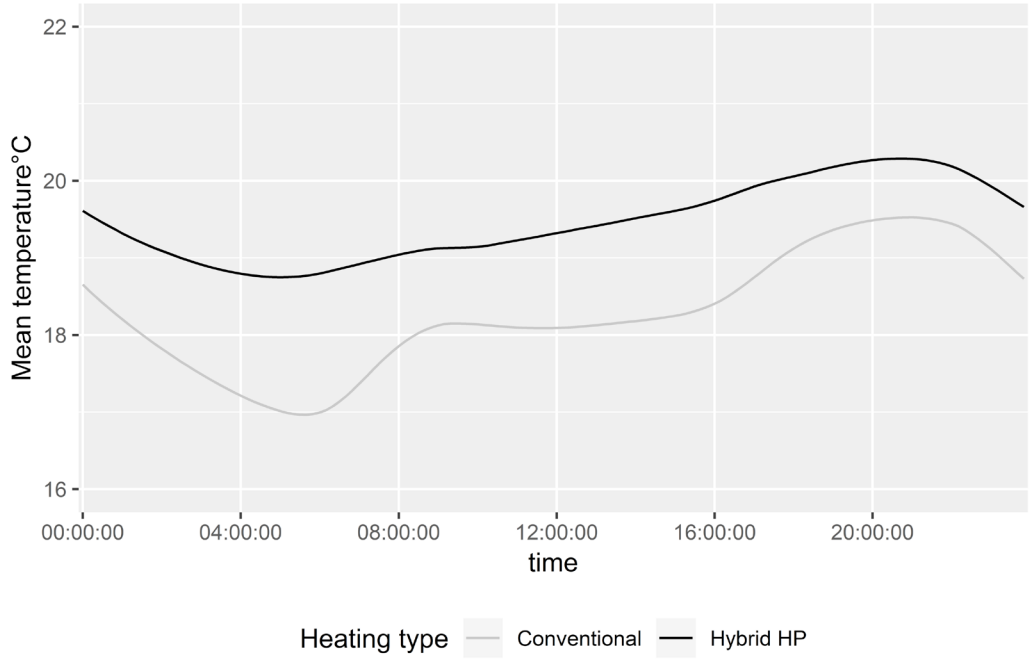


*Figure 1. Mean temperature at thermostat across all the homes in the sample, calculated at 10-minute intervals, weekdays in January and February. Conventional heating: 3,579 homes 3/1/16-27/2/16 (N =133,577 days) Hybrid HP homes: 71 homes in Freedom trial 8/1/18 to 2/3/18 (N=2,096 days).*

Figure 1 shows a comparison of mean daily temperature profiles for the conventionally heated homes and the homes with hybrid heat pumps, for 8 weeks in January and February. The temperature trace for the conventionally heated homes shows a noticeable variation during the day. The lowest temperature at around 5 am is followed by a peak around 09:00, a small dip in the middle of the day and then a steadily rising temperature reaching a maximum at about 21:00. This is similar to the Huebner et al's (2015) analysis of living room temperatures in sample of 275 UK homes, which found that living room temperatures in the evening tend to be higher than those in the morning. The most common "two-peak" profile they identify is very similar to the trace for conventional heating in Figure 1. In contrast, the trace for the hybrid homes shows less overall variation in temperature around a higher mean temperature, but with a clear evening peak.

Patterns of internal temperature will be influenced by the external temperature: when the outside temperature is lower, indoor temperatures will drop faster when the heating is not running. In order to compare the two samples allowing for the varied external conditions that are likely to have occurred at different times and locations, the range of the internal temperature (daily maximum–daily minimum) was plotted against mean external temperature for that day. The points were gathered into "bins" by rounding the external temperatures to the nearest 1 °C and the mean range for each external temperature is plotted in Figure 2.

Figure 2 shows the lower daily internal temperature range for the hybrid HP homes is consistent for all external temperatures. Figure 3 shows that the mean night-time temperature (calculated over the six hours from midnight to 6 am), plotted against the mean external temperature for the day. This shows that the nighttime temperatures in the homes with hybrid heat pumps are consistently higher than in the conventionally heated homes.

Interviews carried out with 11 of the Freedom trialists after their conventional boilers had been replaced by hybrid heat pumps explored their reactions to the changed temperature patterns. Only three of the interview respondents mentioned that they had noticed a change in the daytime temperatures and all these remarked on it favourably. Susan said, "it wasn't too hot and I wasn't cold". Rachel, who reported often being cold with the previous heating system, was very happy with the new installation "it's just constantly warm" and her husband John said "if it keeps on like this I'll be more than pleased".

The response to higher nighttime temperatures was less positive. Of the sample of eleven trialists interviewed, four were unhappy with high temperatures at night. For example, Debbie said "my daughter told me, when she come down the stairs at 3 o'clock this morning, she was boiling and sweating because the heating was on" and Ed complained "the house is constantly so hot … in the middle of the night we wake up with migraines". Two further interviewees said they had noticed higher nighttime temperatures but did not perceive this as a problem.

Ed's case illustrates that initial negative reactions may not be permanent. In a follow-up conversation three months later, he explained he had adjusted TRV and controller setpoints and was happier with the nighttime temperature. It is also possible that, having become more accustomed to the changed thermal experience, he no longer perceived it so negatively.

In summary, residents of homes in the hybrid heat pump trial experienced different thermal conditions to those with conventional boilers. Several reported improved conditions in the daytime but higher temperatures at night were an issue for some. Negative reactions to high night time temperatures in British homes with heat pumps have also been noted by Caird

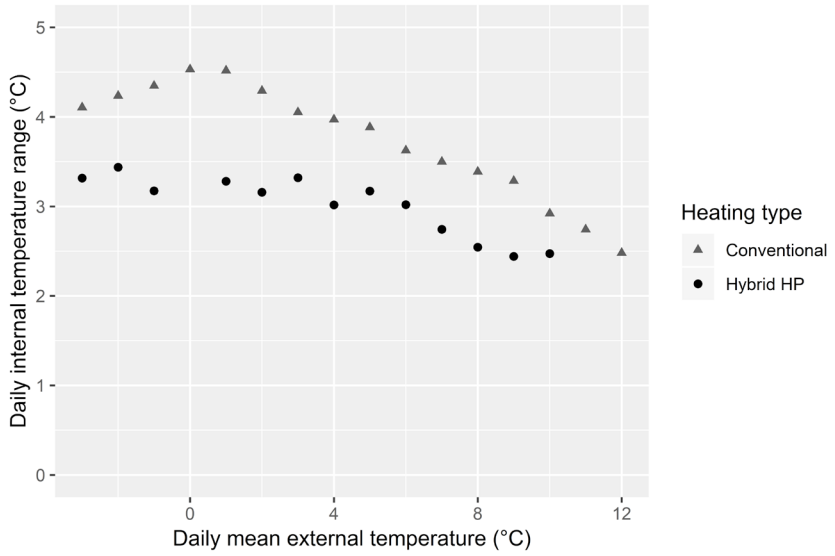


*Figure 2. Daily temperature range plotted against mean daily external temperature, weekdays in January and February. Conventional heating: 3,579 homes 3/1/16-27/2/16 (N =133,577 days). Hybrid HP homes: 71 homes in Freedom trial 8/1/18 to 2/3/18 (N=2,096 days).*

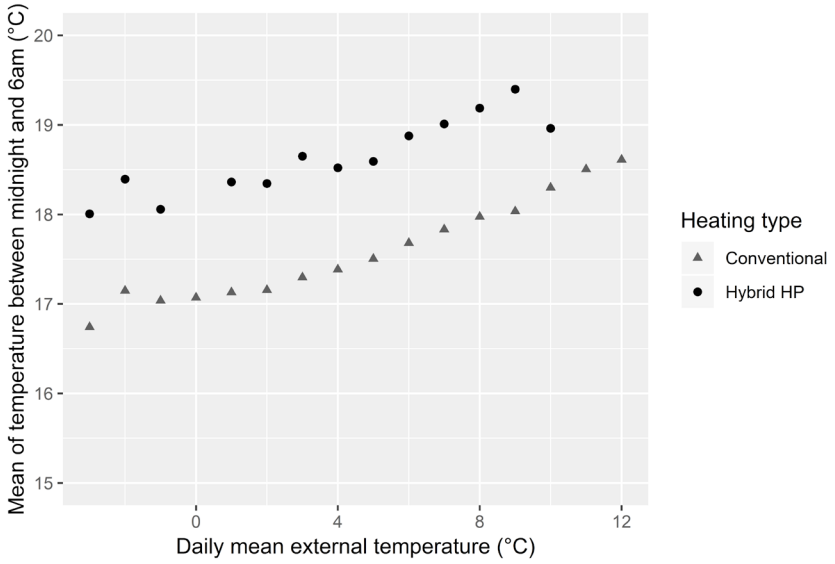


*Figure 3. Mean night temperature plotted against mean daily external temperature, weekdays in January and February. Conventional heating: 3,579 homes 3/1/16-27/2/16 (N =133,577 days) Hybrid HP homes: 71 homes in Freedom trial 8/1/18 to 2/3/18 (N=2,096 days).*

(2012) and Fell (2016). This highlights a potential resistance to heating transition in the UK where people are accustomed to low temperatures when sleeping and may react negatively to higher nighttime temperatures. Heating and building design features such as zoning of bedrooms (so that they can be controlled at lower temperatures) could mitigate these negative reactions.

## Patterns of heating requests

This section examines evidence on the times when residents want their homes to be warm and the variation in temperature setpoints chosen during these periods. Quantitative analysis of heating times and setpoints is combined with qualitative evidence from interviews, which explore the reasons behind residents' choices of controller settings.

### HEATING REQUESTED TIMES

As explained above, the preheating periods resulting from algorithmic control result in the heating operating ahead of the times residents have requested warmth. This can cause confusion about what is meant by "the heating is on" as the times when the heating runs differ from the times the thermostat is at a high setting. In order to distinguish between the times the heating is operating and the times that the residents have requested warmth, this paper introduces the concept of "heating requested period". For those operating a PassivSystems heating controller as the designers intend, these "heat-

ing requested" times correspond to the IN times set in the controller schedule.

When processing the setpoint data, it was found that a minority of both samples were not operating their controllers in the recommended way. For example, they might start the heating running during a period when the controller was set to OUT by manually increasing the setpoint temperature to a higher level (e.g. 22 °C).

In order to include all periods when residents requested warm temperatures as "heating requested" periods, (whether or not the occupancy was set to IN), a threshold temperature was chosen for each home, with any setpoints above the threshold designated "heating requested".

The starting point was to assume a threshold for all homes of 18.5 °C. This distinguishes IN from OUT for those using the default settings of 19 °C for IN and 8 °C for OUT. However some homes never set an IN value as high as 19 °C. A check was therefore carried out to find the most frequently used IN settings and, for homes with IN setpoints regularly below 19 °C, the threshold was adjusted. The new threshold was set at a value 0.5 °C below the lowest regular IN setting. In the example shown in Figure 4b it was set at 15.5 °C. Out of 71 Freedom homes, 53 homes had a threshold at 18.5 °C and 18 homes a lower threshold.

#### TIMING OF HEATING REQUESTS

Figure 5 shows the proportion of homes with "heating requested" (setpoint above threshold temperature) at 10 minute intervals the day. The pattern of heating requests is very similar for the two samples, with a peak in the morning, and a slightly higher peak in the evening. None of the homes appeared to be unoccupied for the whole period, but in many homes there were some days with no heating requested, because the residents were away or had other reasons for not requesting temperatures above 15 °C.

Interview respondents linked many of the scheduled settings to patterns of occupancy in the home, in particular getting up in the morning, going to bed at night, and when they left the building to go to work. However it became clear that residents do not always request heating all the time when they are at home (and not asleep). For example, Debbie was often in the house in the middle of the day, but did not run the heating until her children came home from school: "it's only really in the morning and the evening that the heating is on at all - just when the children are here really. … I'd put the heating on just before say now [14:50] when I go to pick them up from school, but it'll be off all day". When Ed, who sometimes works at home, was asked if he had the heating running at these times he said "typically not. … I might put a jumper on if I need to but it's comfortable". Another example of a respondent who was at home but not running her heating in the middle of the day was Susan, who is generally in during the day but has a scheduled OUT period from 09:00 to 17:00.

These responses suggest that the typical "two peak" pattern of daily heating demand in Britain is not simply driven by occupancy patterns, but also by traditional expectations that heating should run in the morning and evening rather than continuously during the day.

#### MANUAL ALTERATION OF TEMPERATURE SETPOINT

Data for the setpoint at 10-minute intervals was used to detect whether each point was in a heating request period, and if it was, whether the setpoint has been changed manually since the beginning of the period. Changes to a higher value than the initial setpoint were distinguished from changes to a lower value. Figure 6 shows the pattern of these manual changes over the day, as a proportion of all weekdays in all homes in the trial.

Figure 6 shows that at all times of day there have been more manual changes upwards than downwards, and that as the evening progresses the number of homes where the setpoint

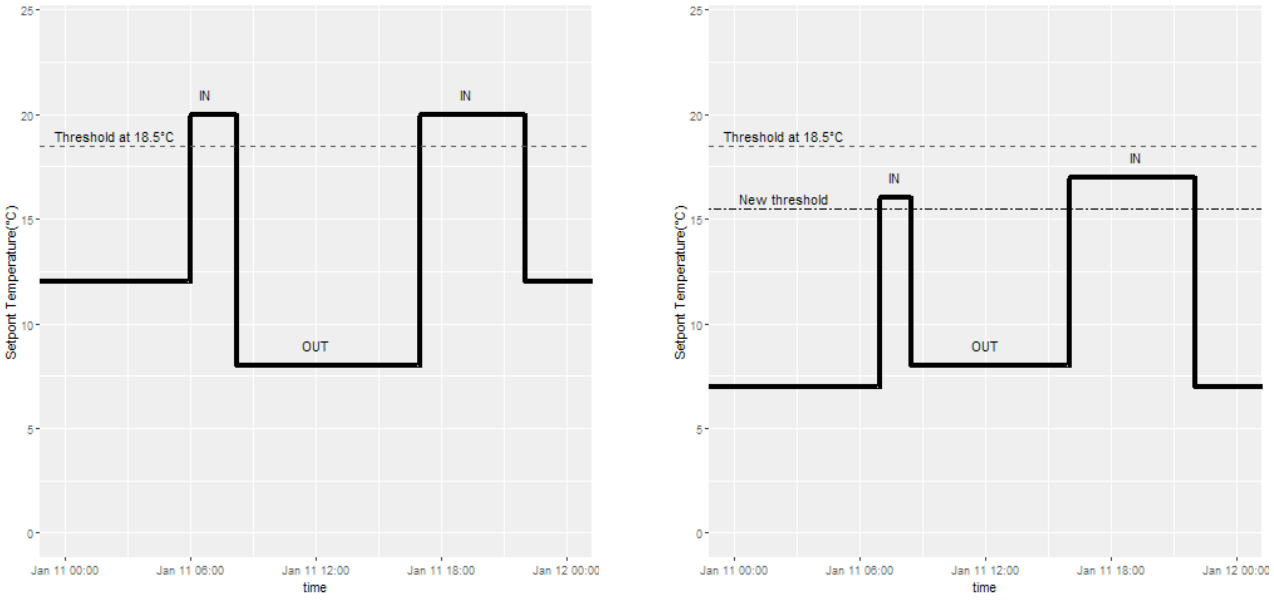


*Figure 4a. Examples of home where threshold of 18.5 °C distinguishes between IN and other occupancy setpoints. Figure 4b. Example of home where the threshold was reset to 15.5 °C.*

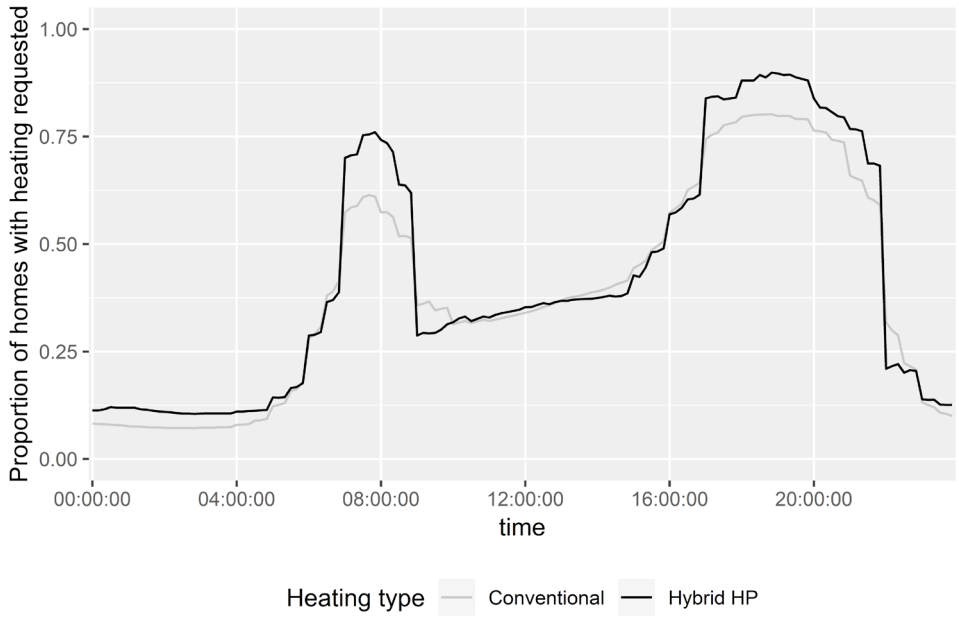


*Figure 5. Proportion of homes with heating requested on weekdays. Conventional heating: 3,579 homes, weekdays 3/1/16-27/2/16 (N =133,577 days). Hybrid HP homes: 71 homes in Freedom trial Weekdays 8/1/18 to 2/3/18 (N=2,096 days).*

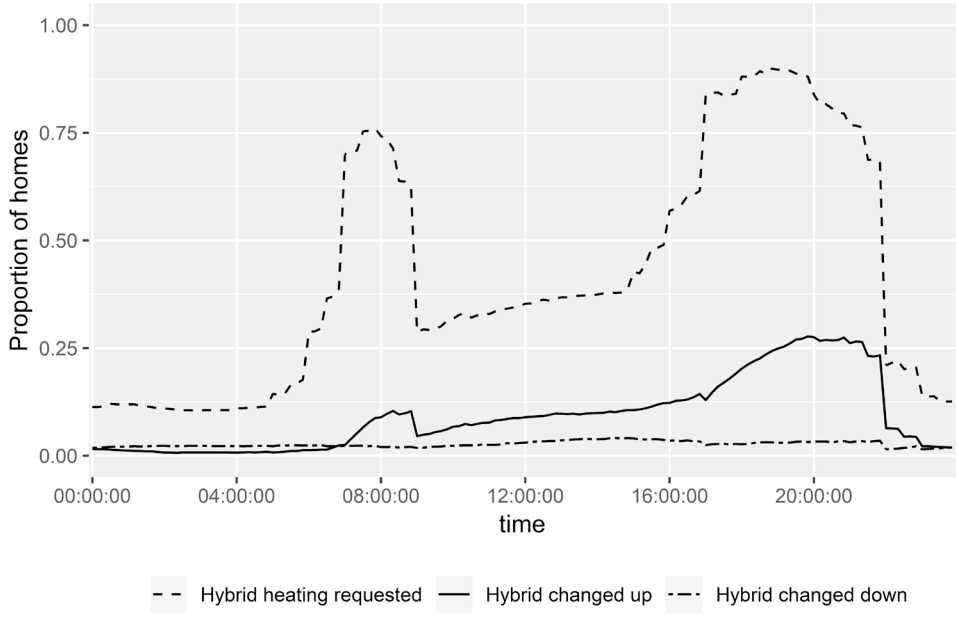


*Figure 6. Proportion of homes with manual changes to "heating requested" temperature setpoint, weekdays only Hybrid homes: 71 homes in Freedom trial 8/1/18 to 2/3/18 (N=2,096 days).*

has been manually increased during the heating period rises until it reaches a peak of 27 % of all homes (31 % of homes with heating requested) at 19:50. These active interventions in the running of the heating are significant for patterns of demand, as a manual increase in setpoint will trigger an immediate demand for heat. The graph shows that these additional demands may well occur in the evening peak period.

The actions taken by Freedom trialists to change their settings can be compared to the sample with conventional controllers. Figure 7 shows that the number of people manually increasing setpoints is not so high but also shows a pattern of an increase to a peak around 8pm.

The participants in the Freedom trial had the option to choose different IN setpoints for the scheduled morning (am) and afternoon/evening (pm) periods. The setpoints in Figure 4b illustrate this – for this home the am IN setpoint is 16 °C and the pm IN setpoint is 17 °C. Across the 8,799 days in the Freedom trial with recorded IN settings 26 % had no set difference between am and pm setting, 45 % had the afternoon/evening setting higher than the morning setting and 29 % had

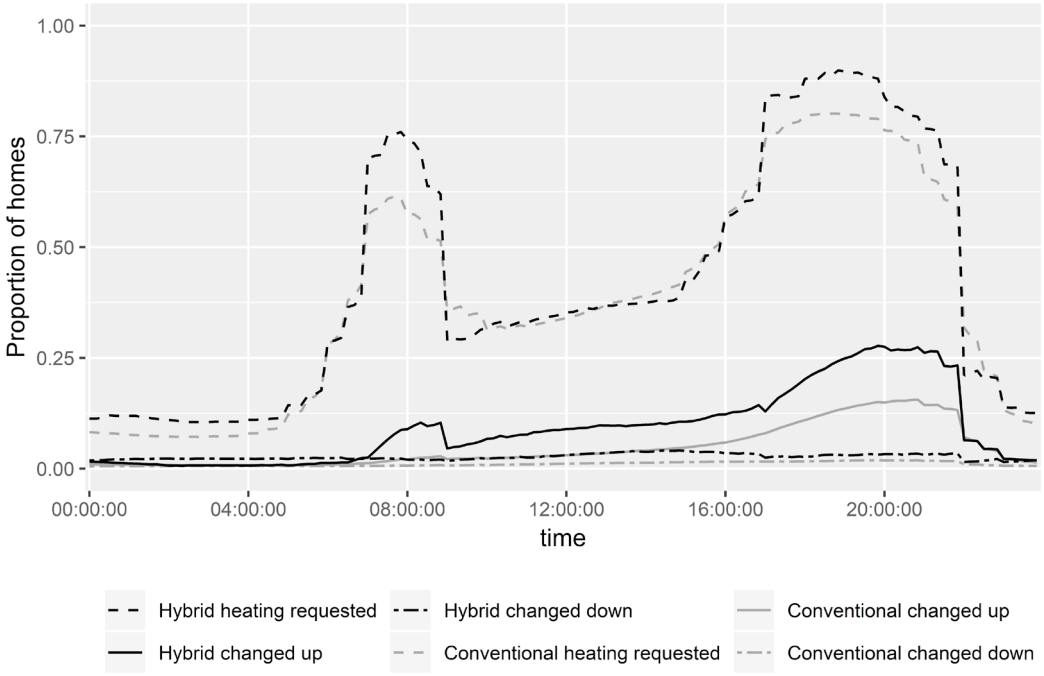


*Figure 7. Proportion of homes with manual changes to "heating requested" temperature setpoint. Weekdays only Conventional heating: 3,579 homes 3/1/16-27/2/16 (N =133,577 days) Hybrid homes: 71 homes in Freedom trial 8/1/18 to 2/3/18 (N=2,096 days).*

pm setting lower than am. This reinforces the impression that a significant number of households (but by no means all) prefer higher setpoints later in the day. These scheduled changes are in addition to the manual changes shown in Figure 7.

The option to select different am and pm setpoints was not available to most of the conventional heating sample so it is not appropriate to compare the two samples on this variable.

Several trialists mentioned different temperature preferences in the evening. For example George (interviewed in the morning) said "I've set it now for 20 and it'll stay that all day and I may knock it up a degree tonight". Chris said "in the morning, because we don't hang around in the morning, it's like a milder temperature in the morning, just to take the edge off it, we all get up, shower, and then we're all off. In the evening we have it a bit warmer".

Chris's mention of different activities provides one possible explanation for different temperature preferences at different times, which is well established in the literature. Thermal comfort approaches, in particular Fanger's Predictive Mean Vote model (Fanger, 1970), suggests that the temperature a person feels comfortable at will vary depending on their metabolic rate and clothing worn. Activity level would seem to influence temperature expectations in the morning when people are "rushing around" and their metabolic rate is higher than when sedentary. When asked why she did not run her heating in the middle of the day, Susan said "When I'm doing things, cleaning, things like that, I don't need it, it's only if I was sitting … perhaps in the afternoon, as the afternoon goes on, I might feel a bit chilly".

A link can be made here to the practices taking place in the home. Shove and Walker (2014) point out that "energy is used, not for its own sake, but as part of, and in the course of, accomplishing social practices". The evening is typically a time for mainly sedentary activities such as watching television while in the middle of the day residents may be more active, moving around to do housework and look after children.

Differing activity levels would not explain why people (like Ed) working from home (sitting at a desk) do not feel a need to "put the heating on" during the day but do request heating in the evening. The adaptive thermal comfort approach suggests that the psychological effect of thermal expectations is another factor to consider and that these may differ at different times of day (Nicol et al., 2012). Many people in the UK are accustomed to higher temperatures in their homes in the evening than in the morning and may have a different view on the acceptable minimum temperature later in the day, associated with the different practices at this time of day. Hong et al (2009) used Fanger's Predicted Mean Vote model to compare reported morning and evening comfort levels reported by residents in 1,130 UK homes and found higher neutral temperatures in the evening than the morning which could not be explained by change in activity or clothing.

It is not possible from the evidence from this investigation to quantify the relative impact of changes in activity level and the expectations associated with practices being carried out at different times of day on temperature setpoints. What is clear is that many households' temperature preferences do vary at different times of day and that a significant proportion of the Freedom sample took action to change their heating setpoint to a higher level at some point as the day progressed. If, following a widespread transition, manual increases in setpoint occurred in many homes at peak demand times, this might reduce the potential for demand management. Unscheduled increases in setpoints could not be matched by pre-heating at periods of low demand since the control algorithm is not able to anticipate changes not entered in advance in the schedule.

## Limitations of the study

The samples may not represent UK households more generally. The households in the conventional heating sample chose to purchase a smart heating controller and the participants in the Freedom trial volunteered to take part. Interviews with a subset of the participants (often only one member of each household) are unlikely to have gathered the full range of responses to the new heating system and may not be representative of a wider population. However the responses do allow some of the issues that could be important for a future transition to be identified. Experiences of, and reactions to, hybrid heat pump operation can be used to inform design and understand how transition can be facilitated.

The configuration of the PassivSystems controller (and the instructions users were given) is likely to have encouraged or constrained particular patterns of operation. The behaviour of residents in the study might have been different with a different controller design.

As explained above, the Freedom trial involved the new heating systems running in a variety of experiments and the actions and reactions of the householders may change over time as they become more accustomed to the hybrid system and encounter less changes in the running patterns of heat pump and boiler.

It should be noted that the reactions to a new heating system described in this paper are the immediate reactions in the first winter of operation. It is widely accepted that practices co-evolve with technical change (see, for example, Shove (2003)). It seems likely that many households will adjust over time and start to change their expectations in line with the performance of the new system, and elements of the initial reactions may prove to be transitory.

## Conclusions

Many UK households are accustomed to running their heating in the morning and evening with no heating operating at nights or in the middle of the day. This operating pattern is expected to change if there is a widespread transition to hybrid heat pumps, as optimal operation (lowest cost for households, avoiding peaks on the electricity grid and periods of high carbon intensity of electricity) requires pre-heating ahead of the times that residents want their homes to be warm. This pre-heating is an important element in ensuring satisfactory warmth from heat pumps and in smoothing the peaks of demand. It leads to a disconnect between times when the heat source is operating and times when residents want warmth, which is an unfamiliar situation for many British households.

Data from homes in a trial of hybrid heat pumps shows there is more consistent temperature in the home over the day than for homes with conventional boilers. This new consistency in day time temperature experience was not a concern for the subset of 11 trial participants who were interviewed. However, warmer temperatures overnight were a concern for several of the respondents.

The typical experience in homes during the heating season is of varying rather than constant temperatures. Not only are people in the UK are accustomed to the temperature in their home varying over the day as a result of intermittent operation of boilers, but also many actively request higher temperatures in the evening than they do in the morning. Interview data suggests that changing temperature requirements are linked to different practices and activity levels at different times of day.

Future scenarios including electrification of heat combined with demand management to reduce peak demands often implicitly assume that changed patterns of heating will be acceptable to households as long as a constant temperature (specified by the residents) is provided at the times they have requested warmth. This study suggests that the actual situation is more complex. The temperatures outside the heating requested period are also of concern to residents (particularly at night) and many households request different temperatures at different points in the heating period rather than being satisfied with a constant temperature.

These varying temperature requirements have implications for energy policy since they imply that heating demand cannot always be shifted, but may be restricted by preferences for specific temperatures (low at night and high in the evening). Plans that envisage heating demand shifting to minimise peak loads on the network should take into account the point of view of households. These may have limits on how far they are prepared to allow heat to be delivered at different times to the periods when they have requested warmth. Heating control design should take into account the varying temperature preferences of residents at different times of day. Controllers that allow residents to pre-schedule different temperature setpoints at different points of the day would allow more flexibility for demand management since the scheduled temperatures can be met by pre-heating, while manual increases in temperature setpoint will trigger an instant demand for heat.

The findings of this study are also relevant for building simulation. It is common in modelling energy demand to assume a constant "demand temperature" for fixed periods when the home is occupied. Data on the variability of actual requested setpoints could be used to improve the accuracy of simulations.

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