Living with demand response: Insights from a field study of DSR using heat pumps

Adria Martin-Vilaseca
UCL Energy Institute
Central House, 14 Upper Woburn Place
London, WC1H 0NN
United Kingdom
adria.vilaseca.19@ucl.ac.uk

Jenny Crawley
UCL Energy Institute
Central House, 14 Upper Woburn Place
London, WC1H 0NN
United Kingdom
jenny.crawley@ucl.ac.uk

Michelle Shipworth
UCL Energy Institute
Central House, 14 Upper Woburn Place
London, WC1H 0NN
United Kingdom
m.shipworth@ucl.ac.uk

Cliff Elwell
UCL Energy Institute
Central House, 14 Upper Woburn Place
London, WC1H 0NN
United Kingdom
clifford.elwell@ucl.ac.uk

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Abstract

Demand response with domestic heat pumps has gained interest in recent years. It is seen as a possible solution to the need to balance electricity grids that are sourcing a higher proportion of their electricity from variable low-carbon electricity sources. Although many modelling studies suggest that demand response with heat pumps will be successful, we have little knowledge of their real-world impacts, including the impact on indoor conditions and the perception of these.

This study compares what happened in three homes of early adopters of heat pumps with demand-side response (DSR). In the three households, the operation of the heat pump was constrained from 4pm to 7pm to provide demand response. Drawing on technical monitoring, we report on indoor conditions in the home and heat pump operation. Drawing on interviews and informed by social practice theory, we explore how comfort at home is experienced and achieved. The focus of the study is on the indoor conditions as the material background for daily practices, and on how these are sensed, interpreted, and created through comfort practices.

The analysis of the results revealed that air and surface temperatures dropped during demand response (air temperature dropped 0.3–1.1 degrees in 3 hours). However, these changes were sensed and interpreted differently by different participants: (1) not perceived, (2) noticed but tolerated without affecting DSR or (3) not tolerated. Although material adjustments were common in (2) and (3), the nature of the adjustment depended on the know-how of the participants and the meaning associated with temperature changes; for example, (2) adopted new materials (e.g., clothes) while (3) changed the operation of the heat pump to produce more acceptable indoor conditions.

The findings challenge conventional modelling assumptions that demand response is unnoticed by people if the indoor temperature remains within the limits of steady-state models of thermal comfort and reveal how demand response is negotiated and incorporated into daily practices.

Introduction

In the last decade, the electricity grid in countries like the UK and the US is sourcing an increasing proportion of its electricity from variable renewable energy sources, such as wind and solar (IEA, 2021a). The adoption of emission reduction targets in multiple countries around the world is likely to accelerate these trends and boost the electrification of several energy services (e.g., transportation or heating)(IEA, 2021b). As a result, the operation of the electricity grid could face challenges that include: a significant increase in total electricity demand (IEA, 2020), the exacerbation of the existing electricity peaks (Love *et al.*, 2017) and increasing difficulty modulating the production of electricity to follow demand (IEA, 2020). Demand-side response (DSR) has gained importance in recent years as an option to overcome these challenges by providing ancillary services to balance the grid (Macdonald, Cappers & Callaway, 2012) and as an alternative to reinforcing the distribution network (UK Power Networks, 2014). Demand response is defined as "changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time" (Albadi & El-Saadany, 2008:p.1990). Various grid services can be provided through DSR, each with different time scales that range from seconds (e.g., frequency regulation) to hours (e.g., load following) (Lee *et al.*, 2020).

The building stock could be a key player in demand response. Buildings can store energy when there is an excess of supply, in the building itself (e.g., thermal mass) or in individual units (e.g., hot water tank), and release it during times of limited supply (Le Dréau & Heiselberg, 2016). The expected widespread adoption of heat pumps for domestic heating and domestic hot water (DHW) in countries such as the UK offers new opportunities to enact it (see Lee *et al.*, 2020, for a detailed analysis of ancillary services that could be provided).

The operation of heat pumps to provide demand response in domestic buildings has been widely studied to try to assess its economic and technical benefits. The literature shows promising results (see Fischer & Madani, 2017, for a detailed analysis), which vary depending on issues such as the control strategy, the limits of temperature variation, the emitters used or the building characteristics (Le Dréau & Heiselberg, 2016). However, most of the studies use models to explore the topic and little empirical work has been done. Particularly overlooked seem to be the role of people on demand response and the effect of demand response on their daily practices. Models often rely on a limited set of assumptions about them: e.g., people are willing to give control of their heat pump (Le Dréau & Heiselberg, 2016) and demand response is tolerable if changes in the indoor conditions do not violate certain temperature limits. Using mixed methods and informed by social practice theory, the present study reports on three case studies of households equipped with heat pumps who tested three different demand response strategies to reduce the electricity consumed by their heat pump between 4pm and 7pm, which corresponds with the current UK peak period.

This paper is structured as follows: Section 2 reviews the existing literature on demand response and thermal comfort and introduces the theoretical framework used, Section 3 outlines the methods and data and describes how they are used to address the objectives of the study, Section 4 presents the findings of the study and reflects upon them, Section 5 summarises the findings and explores the implications for industry and policymakers.

Background

Most of the academics who studied demand response with heat pumps using the building as energy storage have used modelling approaches to the topic (Sweetnam *et al.*, 2019). While these studies bring interesting insights into some of the technical and economic potential of DSR (see Fischer & Madani, 2017, for a detailed review of modelling studies), they have been criticised, among other things, for their limited understanding of thermal comfort (Zhang, de Dear & Candido, 2016) and for their inability to consider the role of people and the interaction between DSR and comfort practices (Sweetnam *et al.*, 2019).

DEMAND RESPONSE AND THERMAL COMFORT

Regarding thermal comfort, the evaluation of the technical potential for DSR in modelling studies is crucially dependent on the boundary conditions defined as representing the limits of householders' comfort. Usually, a certain temperature (comfort temperature) is chosen for each room and used as the thermostat setpoint. Operative temperature is allowed to deviate from this within certain bandwidths before being classed as uncomfortable (e.g., 2 degrees deviation in Reynders, Nuytten & Saelens, 2013). Those limits are usually based on steady-state models of comfort. There are multiple difficulties associated with these assumptions. Firstly, ordinary thermostats do not control heating based on operative temperature and operative temperature is usually not sufficient to understand the thermal comfort of householders. For example, Mishra *et al.* (2016) described how the circadian rhythm of the body influences thermal sensations and temperature preferences, which could affect how demand response is perceived at certain times of the day. Secondly, the use of a steady-state thermal comfort model for a dynamic phenomenon such as demand response has been questioned by Vellei and Le Dréau (2019). Notably, the rate of change of internal temperature is not considered in modelling studies as potentially affecting comfort. This could be problematic since in some cases, steady-state models of comfort are deemed not useful for transient environments: ASHRAE 55 states that temperature changes above 2.2K/hour are usually uncomfortable for people (ASHRAE, 2010).

Several academic studies have attempted to investigate thermal comfort in DSR conditions using empirical research, but their studies largely focus on avoiding cooling demand in summer and do not specifically look at heat pumps for demand response. For example, Zhang *et al.* (2016) carried out several demand response experiments in climate chambers simulating lecture theatre conditions; these experiments used rates of temperature change above 2°C/hour and found participants (students) still to be generally comfortable. A field study in a university building (Aghniaey *et al.*, 2019) concluded that people were generally comfortable when the temperature was increased temporarily from 22 °C to 25 °C – although it was also found that the starting temperature may have been lower than their preferred temperature, which may explain the results. None of these studies studied the periods before and after the peak time window.

While thermal comfort analysis is not commonly found in DSR literature, there is also little empirical work on the role of householders in this process and how DSR with heat pumps is incorporated into daily life. Hanmer *et al.* (2019) and Sweetnam *et al.* (2019) studied heat pumps with external load control for DSR. The former studied hybrid heat pumps (a hydronic central heating system that combined an air source heat pump and a "combi" gas boiler) and found that people have strict temperature preferences at certain times of the day and for some activities and suggested that shifting heating might not be tolerable in some cases, especially in the evening and at night. The latter study investigated the problems of pre-heating in advance of DSR with air-to-water heat pumps with hydronic central heating systems and found people to be concerned about noise and overheating, which affected their capacity to provide DSR. Nyborg and Ropke (2013) explained the intimate relationship between practices and flexibility with heat pumps: participants were more willing to provide demand response when performing certain activities. They also found that motivation, family composition, life situation and technology, are linked to their willingness to participate.

THERMAL COMFORT PRACTICES

Energy consumption is usually the focus of DSR research. However, as Shove and Walker explained "energy is used, not for its own sake, but as part of and in the course of accomplishing social practices" (2014:p.42). Energy peaks are a consequence of the execution of those practices at certain times and the provision of DSR can be achieved through changes in them, being those manually implemented by householders or automatically triggered through the addition of certain technologies. Therefore, the analysis of DSR with heat pumps cannot be separated from the study of daily practices, particularly, from comfort practices at home which require the operation of the heat pump.

The theories of social practices offer a useful and widely used framework for the analysis of these practices (see Gram-Hanssen, 2010, for example). By focusing on comfort practices instead of energy consumption, individuals' thermal comfort responses or measured indoor conditions, these theories could offer some insights into how the social and the material arrangements interact in the provision of DSR and how DSR could affect comfort practices at home. A practice (e.g., comfort practices) is a routinised type of behaviour individually performed and socially shared which consists of several interconnected elements: bodily activities, mental activities, things, etc. (Reckwitz, 2002). Shove and Pantzar (2007) distinguish between practices-as-entities which are provisionally durable nexus of doings and sayings and practices-as-performances which are the performing of specific doings and sayings. Warde (2005) explain that the specific performance of a practice varies between individuals or groups of individuals. The interest of the project is therefore, in the individual executions of comfort practices, and their capacity to transform comfort practices as entities.

Comfort practices (or "heating work" according to Jalas and Rinkinen (2013)) aim to provide the material background for daily practices; that is, they provide the necessary thermal environment for activities in the home (Gram-Hanssen, 2010). In comfort practices, energy flows, governed by people and/or technologies, are controlled to ensure that the desired objectives are achieved: from feeling at the right temperature to minimising the environmental impact (Royston, 2014). People are not passive recipients of certain indoor conditions that can be studied using physiological variables alone (Strengers, 2010); thermal comfort is an ongoing process where people actively create their thermal environment (Hanmer *et al.*, 2017). Thermal comfort is constantly negotiated between the body, the materials and the social (Cole *et al.*, 2008). That contrasts with conventional comfort research as described by Cole *et al.* (2008), which has often approached thermal needs as universal requirements that are determined by physiological factors. For example, Fanger's comfort model (Fanger, 1972), which is one of the most widely used thermal comfort models, is physiologically and individually based and it only uses the following 6 variables to assess thermal comfort: air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation.

THE SENSES IN COMFORT PRACTICES

The need to move beyond physiological approaches to comfort does not mean that the physical experience is not important in comfort practices. The analysis of those practices should certainly include how one feels, senses and delights (Pickerill, 2015). However, while the body plays an important role in social practice theories, Madsen and Gram-Hanssen (2017) believe that the sensorial experience has often been left out of the analysis. The so called "sensual turn" in social sciences has tried to include it by understanding senses as "skills for embodied action and avenues for the transmission of cultural values" (Southerton, 2011:pp.1270–1271). The senses are not neutral channels that connect the external world with the individual; they are an active part of comfort practices. Therefore, Madsen and Gram-Hanssen (2017) understand thermal comfort as a "social phenomenon that is bodily sensed on an individual level as well as shared as social conventions that are interpreted in everyday life at home". At the same time, Royston (2014) argues that senses are involved in the negotiation of thermal comfort and are critical in gaining the know-how used to monitor heat flows in the house.

Methods and data

This project studied a field trial of demand response with heat pumps. The study is exploratory and aims to examine in detail a socio-technical phenomenon in a context-specific setting. Therefore, the research is designed as a case study (Yin, 2017; Bouma, Ling & Wilkinson, 1993) that compares three different cases (comparative case study research as defined by Sovacool *et al.* (2018)). The number of cases studied was kept to three because the focus was on depth rather than the generalisability of the results. The study uses a mixed-methods approach, which includes semi-structured interviews and technical monitoring of indoor conditions and heat pump operation. This paper is part of a larger study and presents the analysis of thermal comfort practices and DSR; there will be a complementary technical paper focussing on the electrical aspects of the field trial of DSR (measuring the impact of different control strategies, the operation of the heat pump during DSR, etc.).

The project aims to analyse the indoor conditions when using heat pumps for DSR and understand how comfort practices are performed during the peak period. The research is informed by social practice theory, and it is guided by the following research objectives:

1. Analyse the changes in the material dimensions of comfort practices during DSR, focusing on indoor conditions during the peak period.
2. Explore the know-how associated with comfort practices during DSR.
3. Explore the meanings associated with comfort practices during DSR.

The data was collected from October 2020 to May 2021. Before commencing data collection, ethical approval was gained from the UCL Ethics Committee and a standard risk assessment and a COVID risk assessment were carried out. Due to the difficulties of recruiting participants during the COVID-19 pandemic, the researchers used a convenience sampling approach. Households are representatives of early adopters of heat pumps for DSR: at least one of the adults in the house had a strong interest in heat pumps and had the necessary skills to program and operate them. All the three cases are in the East or South-East or South-West of England. Table 1 summarises the main characteristics of the cases studied. There exist many types of DSR (e.g., load shifting, frequency response), and in this study we focused on peak

Table 1. Summary of cases studied.

	House A	House B	House C
Household composition	2 adults 1 toddler	2 adults	2 adults 2 teenagers
Heat pump type	Ground source heat pump, inverter control.	Air source heat pump, inverter control.	Ground source heat pump, fixed speed single stage.
Heat pump manufacturer's nominal thermal output rating	15 kW thermal.	8 kW thermal.	11 kW thermal.
House type	End terrace	Detached	End terrace
House age	1905	2011	1936
EPC rating (pre heat pump)	D	B	D
Thermal mass (construction)	High (30 cm solid walls).	Medium (cavity insulated walls).	High (23 cm solid walls).
Heat delivery	Conventional radiators.	Conventional radiators.	Conventional radiators, underfloor heating, and fan assisted radiators.
Implementation of DSR	Changes in temperature setpoint of the Thermostatic Radiator Valves - TRV (15 ºC during DSR).	Changes in the heat pump settings to ensure that the compressor does not run from 4pm to 7pm.	Changes in the central heating flow temperature by changing from normal mode to economy mode (which has a lower heating curve).
Technical monitoring	Electrical consumption of the heat pump (10 minutely) Air temperature in 5 rooms (10 minutely) Radiant temperature in one room (10 minutely) Radiator surface temperature in one radiator (10 minutely) Internal surface temperature in one room (10 minutely)	Electrical consumption of the heat pump (10 minutely) Air temperature in 5 rooms (10 minutely) Radiant temperature in one room (10 minutely) Radiator surface temperature in one radiator (10 minutely) Internal surface temperature in one room (10 minutely)	Heat output of the heat pump (10 minutely) Air temperature in 5 rooms (10 minutely) Radiant temperature in one room (10 minutely) Radiator surface temperature in one radiator (10 minutely) Internal surface temperature in one room (10 minutely)

shaving during the 4pm to 7pm period, which corresponds to the current UK peak period. In contrast to other field studies on the topic (see Hanmer *et al.*, 2019, for example), no additional technologies were used for DSR other than the heat pump. DSR was set up by the participants using three different strategies (e.g., changes in the temperature setpoint, changes in the operation of the compressor, etc.). The demand control strategies chosen could be implemented by an external party and some of them are being used in commercially available DSR programs.

For this project, all the adults living in the house were interviewed. Thermal comfort is individually sensed, and the researchers aimed to capture the diversity of perceptions in each household. The interviews were semi-structured, and they were carried out over video calls, due to COVID-19 pandemic restrictions. Each household was interviewed twice, in Mid-January and at the end of the trial. In some cases, both adults participated in both interviews and in other cases only one adult was interviewed each time. All the interviews lasted between 30 and 60 minutes and they were coded into 16 codes (covering comfort practices, indoor conditions, and senses) using NVIVO. The interviews explored personal experience with DSR (thermal comfort, routines, and activities).

Technical monitoring was undertaken in each home to understand the operation of the heat pumps and the indoor conditions during and around the DSR period. In two homes the electrical consumption of the heat pump was monitored at 10 minutely or higher resolution but in the remaining home (house C) this was not possible; heat output of the heat pump was however available at the same resolution. In addition to outdoor air temperature (10 minutely) several variables representing indoor conditions were monitored and they are described in Table 1. The data was analysed using Python.

Results and discussion

Heat pumps are used as part of comfort practices at home to create the material background for different everyday activities (e.g., maintaining adequate indoor conditions or providing hot water for bathing and showering). People manage heat flows to ensure that heat is where it is needed when it is needed (Royston, 2014). The provision of DSR indubitably shaped those practices, adding more requirements for the heating system (e.g., it is no longer only important to control when and where to heat but also to minimise the electricity consumption at certain times) and modifying its operation. The study analysed how comfort practices changed when DSR was provided, focusing on each of the elements that constitute those practices: materials, competences and meanings (Shove, Pantzar & Watson, 2012). The paper starts by analysing the material conditions for the practice (including technologies as well as indoor conditions), to move towards the role of the householders in creating those conditions (competences and meanings).

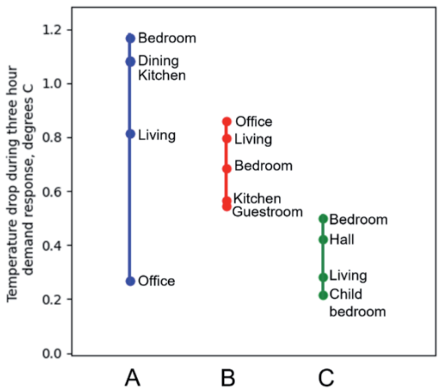

Figure 1. Average air temperature drop during the peak period (4pm–7pm).

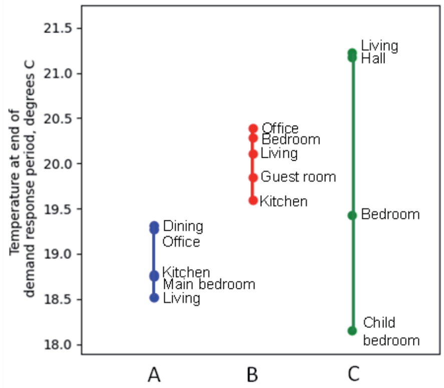

Figure 2. Average air temperature at the end of the DSR period (7pm).

MATERIALS

Two different material aspects of comfort practices have been analysed in this project. On one side, the material objects that are used as part of the practices, including the operation of the heat pump. On the other, the indoor conditions created, which are the thermal background for other daily practices at home.

Material objects and operation of the heat pump

The adaptation of comfort practices for DSR involved several material objects. Participants mentioned the heating system (the heat pump as well as the heat delivery system: the size of the radiators, etc.), the building itself and the clothes that people wore or used to try to create a comfortable thermal environment. Among them, the heat pump, and its operation during DSR remain particularly relevant for the study of comfort practices for DSR. The different means of implementing DSR and the associated change in electricity consumption will be analysed in detail in a complementary technical paper. However, due to its importance in comfort practices, a summary is presented here as follows. In house B, the heat pump compressor was totally switched off, leading to no heat being delivered by the heat pump during the peak period and the house cooling down over this time. In house A, the participants had also intended for the heat pump to switch off for 3 hours, but its internal control logic led it to restart on some occasions, notably on colder days. Thus, there was sometimes a small heat input from the heat pump during the peak period. In house C the system was programmed to reduce the heat pump flow temperature during the peak period, thus the heat pump was still on, delivering a lower amount of heat than usual but not allowing the temperature of the house to drop significantly.

Indoor conditions during DSR

The temperatures dropped over the DSR period in all three homes. On average over the monitoring period, these temperature drops were 1.1 °C (house A), 0.6 °C (house B) and 0.3 °C (house C).

The size of the temperature drop was due to a combination of factors. How much the heat pump operated was likely to be one of the most influential factors, alongside building characteristics of heat loss coefficient and thermal mass. The house in which the heat pump operated the most during the DSR period was the one in which the temperature dropped least, despite being a relatively thermally inefficient house. Internal gains, for example due to cooking, also affected the rate of decrease of internal temperature.

It can be observed that the air temperature did not drop equally across different rooms in each house (see Figure 1). House A had the greatest heterogeneity in the rate of temperature change across the house. That is because one of the rooms, the office, was not heated and therefore its temperature was less affected by reducing the setpoint temperature (only 0.25 ºC). If we omit this room from the analysis, there was a similar heterogeneity in the temperature drop between the studied rooms within the three cases: approximately 0.3 ºC.

The temperatures at the end of the peak period evidence strong differences between cases, particularly regarding the average air temperature indoors and the differences between rooms in each household (see Figure 2). House A reached the lowest average air temperature indoors at the end of the peak period (average air temperature 18.9 ºC). Notably, this house recorded lower temperatures than the others at the start of the DSR period. Similarly, house C had the highest average air temperature at the end of the DSR period, and also at the start. This house also had very different temperatures in each room at the end of the DSR period, which was due to different setpoints used during the day and thus different temperatures in each room at the start of the DSR period.

Wall surface temperature was also observed to drop in each house during the DSM period. Its rate of change was lower than that of air temperature, which is to be expected since surface temperature is more tightly coupled to the large thermal mass of the building structure than air temperature, however the below Figure shows that the surface temperature in one example house (A) still showed a drop of around 70 % that of the air temperature.

These findings regarding internal and surface temperatures lead to interesting implications. Firstly, the different temperature drops observed over different rooms - as well as any different setpoints used in the period leading up to the heating being turned off – imply that DSR could be perceived differently in different rooms in the same house. Secondly, the change in surface temperatures was not negligible and may have some comfort implications. These findings are expanded on in the section below, where it is combined with the participants' stated perceptions and reflections.

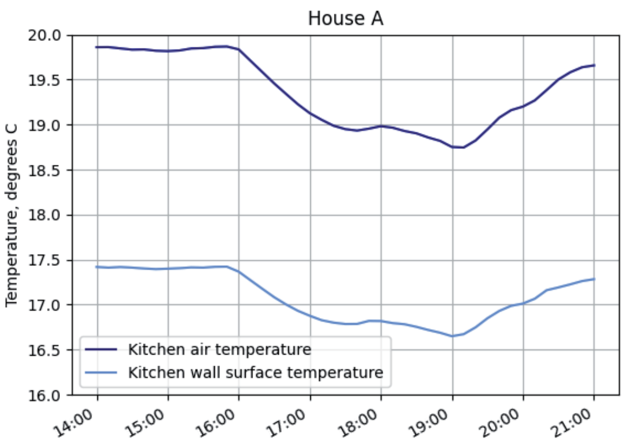

Figure 3. Evolution of the surface temperature and the air temperature in house A. The wall surface temperature dropped 0.7 ºC while air temperature dropped 1.1 ºC.

COMPETENCES

In the previous section, the materials that participate in comfort practices have been explored. People interact with them to generate heat and move it around. The following section explores the competences associated with that, specifically focussing on the participants' know-how or practical knowledge. The study follows the approach developed by Royston (2014), who distinguishes two types of know-how involved in comfort practices: (a) understanding and monitoring heat flows and (b) managing heat flows.

Monitoring heat flows

Royston (2014) explains that people need to understand heat flows and monitor them to be able to manage them as part of comfort practices. However, people do not measure the thermal environment in terms of degrees Celsius or kWh. Thermal conditions are experienced through senses, which mediate between them and practices (Madsen & Gram-Hanssen, 2017). Participants identified various senses which took part in the process of monitoring thermal conditions during the peak period: thermoception (the sense that allows to perceive and regulate heat and cold (Southerton, 2011:pp.1270–1271)), hearing and vision. Regarding thermoception, participants explained that they perceived the temperature drop not only through the temperature of the air surrounding their bodies but also through the surfaces of the objects that they touch (for example, participants in house A could feel the stonework top of the kitchen counter or the radiators to be cold during DSR). In some cases, participants also noticed the sound due to the thermostatic radiators valves (TRVs) opening or closing at the beginning and end of the peak period (case A)[1] or viewed the information provided by the heat pump (uploaded to the cloud) regarding the compressor speed (house B). Those sensorial inputs informed their decisions regarding the operation of the system. The findings evidence that not only air temperature and radiant temperature are sensed, as most modelling studies assume. Surface temperature plays a second role aside from radiative heat exchange, when householders directly touch surfaces and notice their coolth. Noise is also relevant, although in these cases the noise was not problematic because of the timing of DSR but could be more critical during other times of the day, as other studies evidenced (see Sweetnam *et al.*, 2019, for example). Finally, the visual experience of heat flows thanks to the live data available of the heat pump operation was also important for DSR and could become more relevant if smart heating systems become more common.

Managing heat flows

Love and Cooper (2015) found that physical variables do not always explain how the thermal environment is perceived and Cranz (1998:p.113) explained that "people seem to respond more to their ideas about comfort than to their actual physical experience of it". Likewise, this study evidenced that DSR was sensed and interpreted differently by the participants, even when they lived in the same house. The changes were: (1) not perceived, (2) noticed but tolerated without affecting DSR or (3) not tolerated. In some cases, the perception triggered actions that included the adoption of new materials or changes in the operation of the heat pump to produce more acceptable indoor conditions.

Participants in house B did not usually notice the indoor temperature dropping during DSR. The only exception was on a really cold day, and they described this experience as not uncomfortable. However, the male adult noticed changes in the compressor speed during temperature recovery (looking at the live data provided by the heat pump). He realised that on extremely cold days the compressor ran at maximum capacity (the maximum electric power demand of the compressor is 3.5 kW) to try to heat the house after DSR and he was worried that this operation could damage the system. Therefore, he decided to pause DSR for some days to minimise the risk.

Participants in house A noticed the temperature drop but explained that it was "super manageable". They used three main strategies to manage heat during DSR. First, they put on more clothes if they felt cold (e.g., during the interview the female adult was wearing an outdoor jacket indoors). Second, they moved to the warmer rooms within the house, although that was not always possible because in some cases their routines were built around specific spaces (e.g., cooking in the kitchen). Third, they mentioned how, because they know that temperatures drop during DSR, they mentally prepared themselves in advance for the changes. The latter is consistent with Brager and De Dear (1998), who described the importance of psychological adaptation to a thermal environment.

In house C the situation differed. The male adult did notice the temperature drop during DSR but tolerated it. However, the female adult was less comfortable with those conditions, especially at the beginning of the trial. She complained to the male adult, who was in charge of operating the heat pump, and he adjusted the temperature settings during DSR to ensure that the female adult did not feel cold. Therefore, the temperature settings of the heat pump during DSR evolved during the trial through a process of household negotiation. This process of negotiation remains critical, but it is often poorly studied in domestic heating literature (McCalley & Midden, 2004). This is consistent with the approach proposed in Cole

1. The noise originated by the TRVs opening or closing could be due to a too high pressure on the hydronic system, which can be addressed by acting on the circulation pump. Therefore, DSR only affects the timing of the noise, not the noise itself.

et al. (2008) which acknowledges that thermal comfort is not only a physiological state but also a dynamic and participatory process. While the electricity consumed by the heat pump was not measured (see Table 1), adjusting the temperature settings could reduce the amount of DSR achievable; the heat pump was still generating heat through the DSR period at half its total output (compared to the non-DSR period).

Previous studies assume that people are not affected by demand response until the operative temperature drops a standard amount (e.g., by 1 °C or 2 °C in Reynders, Nuytten & Saelens, 2013), or below a certain threshold (e.g., NEDO, 2017) and implicitly suggest that participants will not reduce the amount of demand response provided if this threshold is not crossed. However, as many studies on smart home developments have argued (Strengers, 2013), it was found here that participants are not always passive individuals. Participants were active in the transformation of their thermal environment, through changes in their expectations or surrounding environment (lowering the heating demand) or changes in the heat output from the heat pump (increasing heating demand). Those changes had consequences for DSR. For example, participants in house C did not want to sacrifice comfort and actively opposed the reduced operation of the heat pump during the peak period, resulting in a temperature drop of under half a degree and limiting the amount of demand response provided. Other participants (house A) noticed the air temperature drop of around 1°C (and the surface temperature drop of 0.7 °C) and adapted to it, which contributed to reduce the amount of electricity consumed during the peak period. Further work is required to determine the applicability of standard thermal comfort models to demand response conditions in homes, but our evidence suggests that householders may be more sensitive to the temperature changes than the models assume.

MEANINGS

The primary aim of comfort practices is to provide the thermal environment for daily practices at home. However, other goals might also play an important role in those practices, and they might gain relevance as part of DSR. In addition to thermal comfort, the participants in the trial mentioned the importance of minimising environmental impact, saving money, and feeling in control of the heating system.

Feeling at the right temperature or having an adequate thermal environment was an important goal of comfort practices with DSR. The differences in the expectations that participants had of those conditions were affected by two issues: the participants' previous experience of low indoor temperatures and the activities that they were carrying out during DSR. First, both adults in case A explained how their history of low temperatures at home affected their tolerance to DSR indoor conditions: they were already accustomed to temperatures similar to those achieved during DSR and they were used to wearing many clothes indoors. Second, participants always mentioned the activities in which they were engaged when describing their satisfaction with the indoor conditions. For example, the female adult in house A described how she found the temperatures a bit cold when she was engaging in quiet activities, like reading books with the toddler. Both aspects affecting thermal expectations (experience and activities) have been widely reported in the literature. The former has been studied by academics within the adaptive comfort tradition (see Brager & De Dear, 1998, for example), who showed the effect of thermal expectations on thermal comfort. The latter is widely represented in steady-state models of comfort, such as Fanger's model (Fanger, 1972), which acknowledge the importance of metabolic rates in comfort requirements (quitter activities usually have lower metabolic rates). However, those aspects are poorly represented in modelling studies of DSR, which often consider people to have static temperature needs.

Reducing the environmental impact of the household was also one of the goals that participants tried to achieve with comfort practices. However, this extended beyond implementation of DSR, affecting how they ran the heat pump more widely. Participants in cases A and B mentioned how after adopting the heat pump they decided to increase their temperature setpoints because even after this change, their environmental impact would be lower than with the previous heating system. The adoption of the heat pump gave them the licence to choose certain temperatures that they would not have chosen when using a conventional gas boiler. DSR was also seen as an environmentally beneficial action that could reduce the environmental impact of the household. Some of the participants more in favour of DSR used this argument to justify their behaviours: they explained that that was the reason why they were more tolerant to temperature drops or more willing to adopt certain strategies to manage heat flows (e.g., adding more clothes).

Finally, some participants emphasised how their willingness to change comfort practices was determined by the fact that they actively decided to participate in the trial. Feeling free to participate was an important motivation for some of them. On the contrary, the female adult in house C, who found herself in the trial without willing to participate (it was her husband who signed up for the trial), explained that she saw DSR as her husband's game. She felt cold in some cases and was reticent to limit heating during DSR or to adapt her comfort practices, which reduced the amount of DSR provided. The findings resonate well with Fell *et al.* (2014) who, despite using a more individualistic approach to the topic, identified that reduced opportunities to choice, which affect perceived control, could make DSR less attractive for certain groups of people. In addition, Schweiker *et al.* (2018) have demonstrated how the sense of control affects the perception of thermal conditions.

Conclusions

Domestic demand-side response with heat pumps is seen as a potential solution to the need to balance the electricity grid in a context of widespread adoption of renewable energy sources and the electrification of several energy services. The potential of DSR to contribute to this task has been widely assessed in modelling studies. However, not much research has explored what are the impacts that this technology could have on thermal comfort and daily practices at home. Through the analysis of three homes of early adopters of heat pumps with demand response, we have challenged some of the ideas behind models of DSR, particularly around thermal comfort, and the role of householders. The paper identified some aspects that need to be addressed if DSR with heat pumps wants to become widespread and provides a conceptual framework and approach that could be very useful for future studies on the topic.

The study found that during the peak period (4pm to 7pm), the air temperature dropped between 0.3 ºC and 1.1 ºC and was affected by changes in the operation of the heat pump, the efficiency of the building and the internal gains. While these temperatures drop rates never exceeded the limits of steady-state models of thermal comfort (e.g., ASHRAE, 2010), participants were able to notice the changes and react to them, which questions the suitability of those models to study DSR. The analysis of the internal conditions in the houses also documented some poorly represented aspects in modelling studies that could have important effects on the householders' experience of DSR: the temperature drop is not consistent across the houses, the rooms are heated at different temperatures (which affect indoor conditions during the peak period), and the surface temperatures are also altered during DSR.

The study found participants to be active in the creation of comfortable thermal environments during DSR, which challenged the idea that they are passive recipients of certain indoor conditions (Brager & De Dear, 1998). Taking a social practice theory approach, the research identified the materials, know-how (monitoring and managing) and meanings that constitute the doings and sayings of comfort practices during DSR. First, not only thermoception was involved in the monitoring of the thermal environment: touch, hearing, or vision, were also important. Second, participants' role in managing the heating flows included changes in clothing, changes in the rooms used, psychological adaptation or changes in the settings of the heat pump. The latter had obvious consequences for DSR, and it is not usually factored into modelling studies. Finally, the objectives associated with the provision of DSR were diverse and included varying temperature expectations (affected by experience and everyday practices), saving money, reducing in the environmental impact, and the freedom to choose to participate. Those factors are not usually considered in modelling studies or DSR trials and could affect the ability of households to provide demand response. Some of them, particularly those linked to sense of control or choice, might gain relevance if DSR is automatised by external actors.

We also want to reflect on what we learned from social practice theory about providing DSR in domestic buildings. The research evidenced the existing heterogeneity in the performances of comfort practices during DSR: the practices-as-performance. DSR added new requirements to comfort practices that had to be addressed by householders. The lack of experience means that participants had to take a more individualistic path of materials-competences-meanings rather than simply enact accepted comfort practices. The reproduction of these performances might have consequences for comfort practices in the future, consolidating some of the tendencies that this study identified (adaptation to colder temperatures vs reducing the provision of DSR). That could shape the practices of comfort as entities or contribute to creating specific comfort practices for DSR, clearly differentiated from conventional comfort practices.

The paper has confirmed the importance of householders in DSR, which contrasts with the lack of research on the topic and evidences the need for more field trials of DSR with heat pumps. The study also identified some gaps for future research to address, particularly around the need to better acknowledge the material aspects of comfort practices with DSR (importance of the building, the heat pump operation, clothes, etc.) and the experience of the temperature recovery period (after the peak period). Additionally, more research is needed to identify the groups of individuals with specific performances of comfort practices with DSR that could let to changes in the practice as an entity.

Policymakers and DSR providers wishing to implement DSR should be aware that users have an active role in the provision of DSR, which should be considered. Beyond the existing limitations in modelling studies and in the widespread understanding of DSR that the research has evidenced, the findings could be useful to create new DSR offerings more relevant for households (e.g., offering partial demand response to participants not willing to change their current thermal environments during DSR or reinforcing the idea that DSR could reduce the households' environmental impact).

This research has several limitations that should be acknowledged. Because of the reduced size of the sample of households studied and the exploratory nature of the project, it is not possible to generalise the findings in a wider population and the list of issues identified is not exhaustive, which calls for more research on the topic. The population studied represents early adopters of the technology and people less interested in heat pumps for DSR might face different challenges when adopting it. Additionally, the range of buildings and households studied is limited (e.g., there are no households inhabited by elderly people), which inevitably shapes the results.

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