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Shifting is an energy-conserving interaction strategy for moving energy consumption to times where it is sustainably favorable. This interaction strategy is attracting increasing interest within sustainable HCI studies. While most of these consider how interactive technology can change household behavior, only few report on how shifting is experienced in everyday life when assisted by automation. In this study, we investigate an interactive technology that assists households to shift electricity consumption to times when electricity is cheap or more sustainable. Our study was conducted as a long-term field deployment for 6 to 18 months with eight households, each living with an interactive prototype that shifts running times for a heat pump within user-defined boundaries. Our findings show that managing heat pumps towards assisted shifting was well-received by all households because it was a convenient way to shift electricity consumption. Shifting electricity use facilitated price savings of 6.8% to 16.9%. Nevertheless, our findings also reveal a conflict between the system design, and how householders actually interact with their heating system and experience assisted shifting. Based on the eight households' experiences we present three overall themes of *convenience, control,* and *complexity* that each describes different aspects of long-term real-life use of automatic technology assisting households to shift electricity use. We discuss the broader implications of these findings and the role of design and future sustainability technology in everyday life.

CCS Concepts: • Human-centered computing → Human computer interaction (HCI) → **Empirical studies in HCI**

KEYWORDS

Sustainability; electricity use; domestic; heating; field study; long-term; interaction design; mobile

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1 INTRODUCTION

Sustainability has received much attention from the interaction design and HCI community in the past decade. Within this research work, studies have focused on raising awareness about energy consumption through eco-feedback [27,34,68] and eco-forecasts [33,57,63] in an effort to persuade people to change behavior. Although these studies show that feedback and forecasts can be informative ways to notify people about their energy consumption and the benefits of maintaining sustainable routines, they also demonstrate limitations in achieving desired change [11,23]. Within this research effort, there is little doubt

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that our knowledge base on sustainable HCI contributions is growing within the community [36]. However, to contribute more significantly to this body of knowledge, a suggested next step by Silberman et al. [62] is to: "build, support, and shape systems people use in their everyday practices and do studies that inform the design and operation of such systems" [62].

Today there are numerous large scale projects that build solutions to widespread sustainable problems [13], including shifting [26]. Shifting is an energy-conserving interaction strategy that involves moving energy use in time or place [51]. This need to shift consumption stems from an increased use of energy produced from renewable resources such as wind and solar power and changing demand profiles that generate fluctuations in the power grid. Smart grid technology is often portrayed as a supportive technological means to overcome these fluctuations. Electric domestic heating powered by heat pumps is anticipated to play a significant role in realizing smart grid scenarios because heat pumps are seen as high consuming, but an energy efficient appliance capable of integrating smartly with the power grid [41,46].

Although much effort has gone into developing smart grid technology, two areas of critique have inspired our work. Firstly, little attention has been placed on how people use and experience these technologies in residential and everyday life [31,52,68]. Secondly, only a few user studies [10,14,16] report on how shifting, and in particular assisted shifting, is experienced in a real-life setting long-term. Hence, as a community we need more insights into how households experience smart grid technology assisting them to shift consumption in real-life settings, so we are better equipped to shape the interaction design for these scenarios in the future [62].

The purpose of this study is to address these research gaps by investigating the long-term experience of assisted shifting in a real-life context by studying a prototyped smart grid technology, named HeatDial [30]. The work presented in this paper extends an earlier study [30] where we introduced the design of the HeatDial system and gathered initial feedback on the interface from a small group of users. In this paper, we provide a different perspective, where we look closely at how householders experience the short and long-term impacts of living and interacting with a smart grid technology assisting them with shifting heat pump electricity consumption. For this purpose, we systematically studied assisted shifting through the HeatDial system with eight households over periods of 6 to 18 months. The study is set in Denmark, where electric heat pumps and smart grid technology are viewed as important means in the transition towards an electricity production reliant solely on renewable resources [20,47]. The HeatDial system assists households to shift their electric heat pump consumption to times when electricity is cheap or renewable electricity is produced. To do so, households need to specify temperature boundaries, and the prototype will then automatically shift electric heat pump consumption in time, while maintaining the temperature of the home within these boundaries. Our study makes two overall contributions to HCI: 1) a long-term real-life study of the experiences of people living and interacting with a smart grid technology, and how this affects them and their households in the short- and long-term. 2) Empirically-based insights into the use and experiences of assisted shifting in heat pump electricity consumption expressed through three identified themes of *convenience, control,* and *complexity.* Additionally, we discuss our findings in relation to future design of smart interactive technology aiming to tackle sustainability challenges in everyday life. In particular, we illustrate the tension between calm and proactive technology for assisted shifting and electricity use.

2 RELATED WORK

Shifting domestic household electricity consumption is increasingly being investigated within the sustainable HCI research community. Shifting is part of what Pierce et al. [51] call a vocabulary of energy-conserving interactions. Within this vocabulary, shifting is seen as an interaction strategy for using energy at a different time or place, to overcome fluctuations in the power grid. Shifting is often used in relation to smart grid technologies and dynamic pricing schemes.

The smart grid is a broad term often used to describe visions for future electricity grids that are more intelligent, interactive, and capable of better balancing fluctuations in power usage. The transition into this future demands not only new technology but also upholds an expectation that households will become active participants in integrating this technology into everyday living [31]. The vision of aligning domestic living within a shifting strategy is often conceptualized through dynamic pricing schemes. Here, market mechanisms are expected to encourage household members to change behavior according to real-time electricity prices.

The impact of embedding smart grid technology and dynamic pricing schemes into domestic living has been studied in various HCI studies [7,8,10,17,57]. However, this perspective on shifting has also been critiqued, particular within social science studies [13,26,29,46,65]. These studies often argue that the design of smart grid technologies are better suited to fit Strengers' Resource Man — an archetype empowered by this technology who adjusts his behavior accordingly — rather than how everyday life is actual performed [66,67]. While this body of work shows that there is a potential for smart grid technology to make us more sustainable, it also highlights a need to broaden our understanding of the implications of embedding such technology into everyday life and the role of interaction design and HCI in facilitating this [31,52,62,68].

2.1 Sustainability Through Monitors and Managers

Home energy systems aiming to support householders to act sustainably can be divided into two main categories; monitors and automatic managers [18]. Monitors are systems that monitor consumption and through feedback inform households by raising awareness, but leaves the actual action to the householder, while automatic managers assist householders to control how energy consuming devices operate.

Systems that monitor and provide feedback are often adopting some form of persuasive technology [27]. Persuasive technology has its root in behavioral psychology and assumes that given the right information, people will change their behaviors. Most studies pursuing the energy conserving-strategy of reduction have done so by visualizing past and present consumption to prompt behavioral change – also known as eco-feedback [27,34,35,58]. Similarly, recent research work has explored shifting through eco-forecasting, where predictions of consumption, cost, and grid demand are visualized on situated displays to indicate the 'right' time to use electricity [33,49,57,63]. The effectiveness of utilizing persuasive technology to advocate sustainable behavioral change has been studied within sustainable HCI research for over a decade [11,23]. This work has shown that, as a community, we still have much more to learn about how we can make use of technology and interaction design to influence householders to develop and maintain sustainable energy-conserving routines and practices [24,31,39,52,68].

Recently, sustainable HCI research has also studied automatic managers that prototype different smart grid scenarios aiming to shift domestic activities that consume electricity. An example is the activity of doing the laundry studied by Bourgeios et al. [8] and Constanza et al. [17]. In both these studies, the objective was to actively assist householders to shift the timing of laundry activities to align with renewable energy production. To assist in planning and executing laundry activities, both studies investigated the possibilities of automatic managers playing an active part in both informing and controlling when it was the right time to wash. Another example of prototyping a smart grid scenario is Alan et al.'s [2] field studies of two different prototypes that allow householders to choose different levels of automation that assist with shifting energy tariffs simulating a dynamic price market of electricity. While their results demonstrated a promising potential of householders being willing to adopt intelligent energy systems into their lives, their studies also highlighted a design challenge of balancing user and autonomous control.

Recently, assisted shifting has been studied with respect to charging electrical vehicles (EV's). Brush et al. [10] did an experiment where they measured the effectiveness of shifting EV charging to off-peak times while utilizing the EV's battery for household consuming activities during peak times. Similarly, Bourgeios et al. [7] explored shifting in relation to EV use and people's willingness to align car trips, charging times, and solar power production. In this study, it was found that planning household tasks to accommodate flexibility to allow for shifting daily routines is a complex endeavor that requires management and negotiation amongst different householders and between different domestic activities.

2.2 Informing and Assisting Householders to Conserve Heat

Designs for both informing and assisting householders and workplaces to conserve heat have also been studied within sustainable HCI. An example of informing users to conserve heat through design is Constanza et al.'s [16] three-week workplace study of regulating heating by giving feedback on temperatures rather than the actual energy consumption. Their results showed that information visualizations can get people engaged with existing heating patterns through reflection.

There has also been an increased interest to study different types of intelligent technology aiming to assist households to adapt indoor heating towards sustainable use of energy. An example is Fischer et al.'s [25] study of using intelligent technology to gather information about the indoor climate, which was proven useful for energy advisors. Preheat [59] and TherML [37] are other prototype examples of intelligent technology that without any direct user involvement can predict when people occupy their houses and then heat based on occupation patterns facilitating a reduction in energy consumption.

Similarly, The Nest is a commercial thermostat that aims to reduce consumption related to heating and cooling by deriving user preferences intelligently. Yang et al. [70–72] did an extensive user study of the Nest. They observed that while the Nest manager played an active role in assisting householders to adopt sustainable routines, conflicting user and system objectives dampened the effectiveness of maintaining these. In response, the same authors developed the ThermoCoach prototype [73], promoting eco-coaching (personalized recommendations, eco-forecasting, easy invocation, and user control) assisting users to continuously reconfigure the Nest to reduce consumption.

There are also a few HCI studies that have experimented with intelligent technology with the goal to challenge people's thermal comfort in order to shift consumption. One example is Clear et al.'s [14] study of 'drifting' thermal comfort zones facilitated by assistive technology. In this study, the authors report on positive results on letting intelligent technology assist in motivating and engaging users towards sustainable heating habits, but they also discovered design challenges in how to reshape existing norms and expectations of indoor heating. Another example is to operate heating devices after cost explored by Alan et al. [1]. In their study, they examine how users perceive trading comfort for a price, as they correlate each temperature with a cost. In SmartThermo [1] users can actively decide what temperature they prefer based on these dynamic prices or let the system derive preferred settings through machine learning. Although they reported limitations on how users perceive the different models, they also discovered that by deploying prototyped smart grid technologies into a real-life setting, they were able to provide valuable insights into how people adopt, perceive, and experience future scenarios and technology. Pink et al. [53] suggest a more practice-oriented lens to approach sustainable interaction design that challenges domestic heating practices. In this study, the authors demonstrate how sensory ethnography can be utilized as an analytic framework to understand how material and social elements of people and environments can inform a sustainable interaction design.

3 FIELD STUDY

The contribution of this paper is a field study done with eight households that used the HeatDial system to control residential heat pumps to warm the inside of their homes. Our aim was to study assisted shifting in an everyday residential setting over an extended period to broaden our understanding of how householders respond to using an interactive system that shifts electricity consumption on their behalf. The study was conducted as a long-term field deployment where half the households participated for 18 months, while the other half participated for six months after being added to the study after 12 months (see fig. 2). In the following, we present background information on electric heating in Denmark, the design rationale of the HeatDial system, a description of the eight participating households, and a description of the study design.

3.1 Electric Heating in Denmark

A heat pump is a device that utilizes heat variations and electricity to transfer heat to either cool or heat a place. In Denmark, most domestic heat pumps are used for heating the indoors by transferring heat from the external air or ground to an internal sink of heated water. The heated water is typically circulated through a bigger heating system where the water runs through the floor and radiators, effectively heating the house or used as utility water for showering etc. It is common to expect four weather seasons in Denmark with frosty winters and moderate summers. This means that most heat pumps will heat the house during autumn, winter, and spring, while only being used to produce utility water in the warmer summer months. A heat pump regulates the temperature through technology that is already semi-automated. The most common scenario is that the technology will aim to keep the same temperature specified by the household. Most Danish heat pumps homes are found in rural and outbound city areas as these property owners must acquire and manage their own heating system. Buying a heat pump in Denmark is a relatively high-cost investment, often done in relation to larger energy-efficient renovations. Consequently, most Danish heat pump homes are also well-insulated, which can result in long response times when households regulate the temperature.

Together this means that heat pump homes will consume large amounts of electricity as their heating is produced by using electricity. Thus, choosing a heat pump for heating in a Scandinavian climate may appear unsustainable as households will significantly increase their overall electricity consumption. Nonetheless, electric heating and heat pumps play a significant role in future Danish smart grid visions and the transition towards a greener energy production [20,47]. The reason for this is three-fold. Firstly, electric heating is an attractive form of heating if the electricity is drawn from renewable resources like wind and sun. Secondly, as Danes have become accustomed to a stable power grid, the heat pump is an attractive device to exploit in a smart grid scenario that aims to balance fluctuations [47], because the heat pump's controllable features make it possible to align the running time of heat pumps to when environmental friendly wind or sun power is produced [44]. Thirdly, in 2012, the Danish parliament approved an ambitious green transition plan promising to deliver 50% of the nation's electricity from wind power by 2020 [20]. The Danish government also backs the transition towards electric heating financially, by subsidizing some of the cost of every consumed kWh that is above a yearly threshold of 4000 kWh in homes that are electrically heated. Based on these reasons in Denmark residential electric heat pumps are seen as a green alternative to fossil fuel-based systems like oil furnaces or wood pellet boilers.

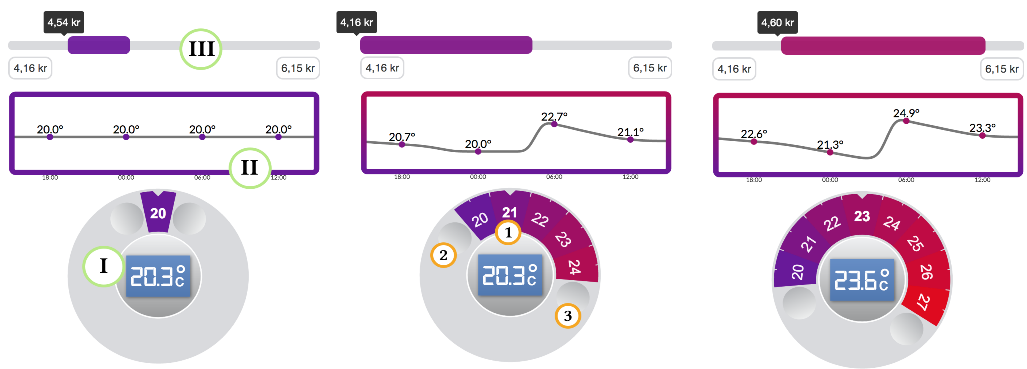
3.2 The HeatDial System

While our prior work [30] introduced the initial design of the HeatDial system and the underlying technical platform, we will in the following present and add more specific details to our design rationales behind HeatDial. Inspired by Yang et al. [72], our objective with the HeatDial system was to create a "mix-initiative system that primarily allows users to pursue their own individual and immediate goal of comfort within certain system-defined bounds" [72]. However, unlike the Nest Thermostat [71] that intends to reduce energy usage, the aim of the HeatDial system is to assist households to move or shift energy usage to times where it is sustainably favorable. This is a different challenge to get householders engaged in, because shifting requires different behavioral patterns than those related to reduction [50].

To address this design challenge, HeatDial is a two-part system: an interactive web application that runs on any type of mobile device, and an automatic manager controlling the running time of a heat pump. The automatic manager is distributed between an in-house control system and a centralized heat pump server that calculates optimized running times for the individual houses. A local smart grid technology company (here referred to as NG) had the responsibility of developing and maintaining the automatic manager for this study. For further details about the technical architecture of the system, please refer to [30].

3.2.1 User Specified Boundaries and The Automatic Manager.

In the interactive HeatDial interface, users can specify three temperature settings (fig. 1B). The first temperature is a preferred temperature (21°). This setting works as a user-specified ideal temperature for the home. The second temperature (20°) is a lower boundary temperature, and the third temperature (24°) is an upper boundary temperature. The two latter temperatures define a tolerance range (4°), basically specifying their boundaries of comfort, which the users allow the system to operate within. The idea of operating heating boundaries of comfort is often envisioned as one way to engage Danish households in



(1A) (1B) (1C)

Fig 1: HeatDial with three different settings. In 1A the preferred temperature is set to 20° and no tolerance range with a price at 4.54 DKr. In 1B the price has been reduced to 4.16 DKr. due to a larger tolerance range, while the indoor temperature is expected to fluctuate more. In 1C the preferred temperature is raised resulting in an increased price of 4.60 DKr .

shifting and smart grid scenarios [20]. The automatic manager schedules the heat pump to run when the price is lowest on the 24-hour Danish electricity spot market. A low price on the Danish spot market is often an indication that there is a surplus of wind power production. However, as only 15% of the total electricity bill is made up from actual usage (the rest of the cost goes to duty, tax, and subscription [19]), electricity bills in Denmark are rather stable, and only vary slightly as a consequence of electricity market price fluctuations.

Unlike SmartThermo [1] and the Nest [71] that use machine learning to derive individual users' preferences, the HeatDial system uses different information sources to learn more about the individual houses including its householders' temperature preferences. This information includes the three user-specified temperature settings, the 24-hour spot price, different sensor information available from the houses, a thermal model of each house, and a local weather forecast.

The HeatDial system uses this information to regulate the temperature after a shifting strategy that aims to keep the inside temperature as close to the preferred temperature as possible. However, the system will allow the temperature to either drop or rise if a lower price is available within the next 24 hours. The system does so by continuously scheduling running times for the heat pump by using all this information. The three user-specified temperature settings influence this schedule as follows:

(1) If the tolerance range is changed, the automatic manager will try and shift electricity consumption to different times, but only if the price is low and it can keep the temperature within the tolerance range. Hence, if a user chooses a larger tolerance range, the automatic manager will be more likely to find times to run the heat pump at a lower price. In this case, the heat pump will use the same amount of electricity, but the times the heat pump runs will be shifted. This shift may result in temperature fluctuations. Nonetheless, the manager will only alter the heat pump's running times, if it can find a price that is low, and temperature fluctuations stays within the tolerance range.

(2) If the preferred temperature is changed, so is the amount of consumed electricity. In this case, the automatic manager schedules a plan that either reduces or increases the consumption. This occurs because the automatic manager will always keep the temperature as close to the preferred temperature as possible. Hence, if a user chooses to increase the temperature, the heat pump will run more often resulting in an increased use of electricity and vice versa.

3.2.2 Informing Users of the Benefits and Consequences

The HeatDial interface also provides two types of eco-forecasted information elements, informing users of the consequences or benefits of choosing different temperature combinations. The first element (1A-III) shows a cost price for running the heat pump for the next 24 hours with the current settings. The second element (1A-II) is a visualization of expected temperature fluctuations for a 24-hour period. The latter element was added twelve months into our study. Our preliminary study [30] suggested that although an automatic manager can assist in hiding the complexity of shifting from a user, it is equally important to give some kind of feedback on how the system plans to behave. This insight led to the design of the second eco-forecasted information element that visualizes the expected influence the automatic manager has on the indoor temperature. The HeatDial interface also displays the current temperature (1A-I), so the user has a reference point when exploring different settings.

In addition to the HeatDial prototype, the participating households also had access to the website ‘control-your-heat-pump’, which provides historic and current information about heat pump performance, in-house measurements such as indoor and outdoor temperatures and electricity consumption data, and the amount of heat the heat pump produces.

3.3 Participants

We recruited eight households from Denmark. The eight households were recruited through a user database from a related project on smart grid technologies, where the heat pump had been controlled for other purposes. The requirements for participating in the study were: (1) the households had to use an electric heat pump as the main source for heating the house; (2) the heat pump had to be controllable by NG, the local company specializing in smart grid technologies; (3) they had to have a device with an internet browser for accessing the HeatDial app; and (4) they had to be willing to use the HeatDial app for regulating the temperature of their home.

The recruited households all owned their house, and all lived in rural areas. This meant they were not connected to the city central heating system and therefore responsible for their own heating needs. In order to use a more ‘eco-friendly’ source of electricity, they had all purchased their heat pump five to six years ago as an investment upgrade to their heating system. Prior to this, they relied on different fossil fuel devices to power the heating system. Most houses were also well insulated. The householders had used the first years with the heat pump to adjust technical settings – although the approach differed depending on

Table 1: Summary of details describing the individual participating households.

	# Children, # Adults	Age of Adults (F/M)	Occupation (F/M)	Location of floor heating	Wood burner	Solar panel	Awareness of heat pump behavior	Environmental motivation	#Winter seasons, #Months
Household A	(2,0)	(70, 69)	Both retired	Living room	Yes, regularly	No	Limited	Normal	18 (2)
Household B	(2,4)	(35, 34)	Project leader Mechanical engineer	Downstairs and upstairs bathroom	Yes, occasionally	Yes	High	Normal	18 (2)
Household C	(2,0)	(74, 69)	Both retired	Living rooms	Yes, occasionally	No	High	Normal	18 (2)
Household D	(2,3)	(47, 42)	Correspondent Bank specialist	Living rooms	No	No	Normal	High	18 (2)
Household E	(2,2)	(54, 53)	Health consultant Social educator	Basement	Yes, rarely	No	Limited	High	6 (1)
Household F	(2,0)	(68, 78)	Both retired	Living room	Yes, occasionally	Yes	High	Normal	6 (1)
Household G	(2,0)	(58, 62)	Nursing Project manager	Bathroom	No	Yes	High	Normal	6 (1)
Household H	(2,0)	(53, 57)	Nurse Sales director	Living room	Yes, occasionally	Yes	High	Normal	6 (1)

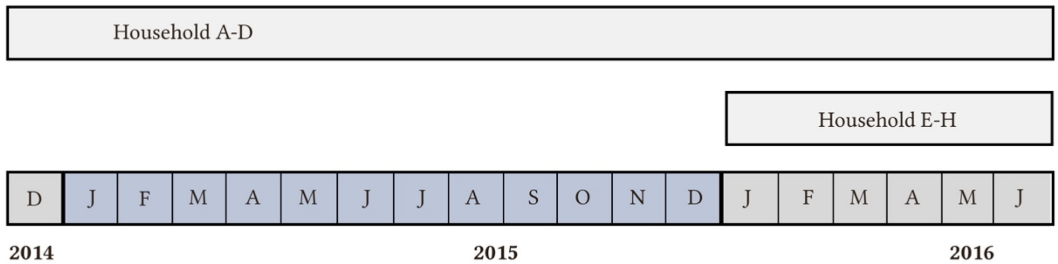


Fig 2: Household participation in the HeatDial study.

how skilled they were in this domain. All the householders were well aware of the amount of electricity they consumed per year. This awareness became an intuitive concern because upgrading the heating system to a heat pump resulted in an increase in the overall household electricity consumption.

To keep an eye on the electricity consumption of the heat pump, they would use both quarterly utility bills and past data from the 'control-your-heat-pump' website. All the houses were equipped with floor heating, mostly just in one room, while radiators would warm the rest of the rooms. Six out of the eight households also used a wood burner as a secondary resource for warming the house, while four households were also equipped with solar panels. We classified five out of eight households as having a high awareness of the technical aspects of heat pumps, while two households were classified as being above average in terms of their environmental motivation. See table 1 for a summary of each of the households.

3.4 Study Design and Data Collection

As our study aim was to investigate assisted shifting over a prolonged period of time, we conducted 20 interviews over 18 months. Households A-D took part in the study for 18 months including two winter seasons, while households E-H participated over six months including one winter season. A timeline of household participation in the study can be seen in fig. 2.

3.4.1 Methods

We started the study with an in-home semi-structured interview with household A-D lasting between 45 and 115 mins. This introductory interview was conducted to gain insight into each household's heating practices prior to the study, as well as giving us an opportunity to introduce the HeatDial system and explain the focus of the study. In the introductory interview, we mainly asked questions regarding the household's current heating practices, how they interacted with and understood their heating system, and their awareness towards environmental issues such as shifting. During the introduction to HeatDial, we explained the different elements of the system and allowed the participants to experiment with the interface, while we were present. This was also an opportunity for participants to ask questions about the system and the study. We explained the purpose of shifting and using electricity at times when it was favorable, and we clarified how shifting was facilitated in the HeatDial system.

During this first in-home interview, we also conducted a conversational technology tour [6]. On this tour, the participants guided the researchers through the setup of their home heating system, the heat pump, and how they currently interacted with the system. There were two reasons for conducting this tour. Firstly, we as researchers gained insight into how individual householders would interact with and perceive this complex heating setup. Secondly, it gave the householders an opportunity to explore and divulge their implicit routines and perceptions regarding their interaction with the system. During the tour, the researchers took notes and photographs of the technology (see fig. 3 and 4). We conducted a second interview with Household A-D after six months, focusing mostly on how the participants experienced the interaction with the elements in the HeatDial interface. Some of this is reported in [30].

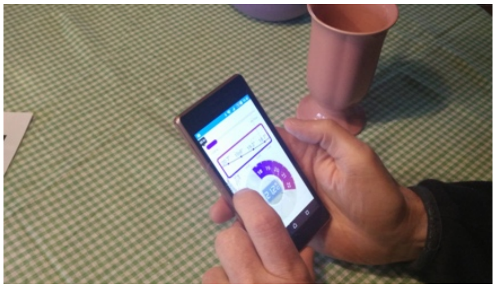


Fig 3: One of the participants using HeatDial on a mobile at the dining table.

Fig 4: An air to water heat pump at one of the participating households.

After twelve months of successful deployment, we decided to recruit an additional four households (Household E to H) in order to gain supplementary perspectives on the use of the HeatDial system. We conducted the same introductory interview with these four households. For practical reasons, mainly due to extensive travel times to people's homes, these interviews were conducted by phone rather than in person. As we had already established a good understanding of household heating practices, these interviews turned out to be very similar to the in-person ones. The interviews lasted between 30-60 minutes. In the same period, households A-D were introduced to the new interface elements of HeatDial.

During the entire study, we logged interactions with the HeatDial system. In the last two months, we also sent out text messages to each household, asking them questions about who and how they used the HeatDial interface, and with information reminding them about shifting features in the system. These logs and answers from the text messages guided the final round of interviews [40].

The last semi-structured interview was conducted during summer 2016. Interviews with Household A-E were conducted in-house, while interviews with Household F-H were conducted by phone. These interviews lasted between 60-110 minutes. As the key interest in this study was to observe households' understandings and perceptions of automatic shifting, we focused these interviews on how the households experienced shifting through the control of the HeatDial system.

In addition to the interviews, we also gathered quantitative data from NG (the company responsible for maintaining the automatic manager) on how the households' heat pumps operated over the duration of the study. This included temperature readings from the house, heat pump power consumption, obtainable price savings, and settings of the three temperatures in HeatDial.

3.4.2 Data Analysis

All the 20 interviews were audio recorded and a total of 21 hours of audio was transcribed using interviewScribe. The transcriptions were subsequently analyzed inspired by content analysis [42]. This was accomplished in four steps. First, we read the transcribed interviews to become more familiar with the data. Second, we identified suggestions for codes inspired by the terms in the literature (e.g. 'comfort', 'feedback', 'assisting'), or through in-vivo codes [42] provided by the participants (e.g. 'roles', 'steering', 'convenience'). Thirdly, we added specific codes to the transcribed interview quotes (e.g. the code for 'feedback' to the quote *"I think about the price because I see a number and it will have an impact on whether the number increases or decreases?").* Lastly, extracted quotes were affinity diagrammed [5] in a repetitive process that led to a set of themes. In the following, we describe three overall themes that illustrate different aspects of assisted shifting experienced long and short-term in a real-life context, namely; (i) assisted shifting as convenience, (ii) staying in control, and (iii) complexity of heating in real-life.

4 FINDINGS

Our findings stem from all 20 interviews with the households, interaction logs, operation data from the heat pumps, and measured indoor temperatures. While regulating the indoor temperature is not something that is done on a regular basis in Denmark, we still logged a total of 940 interactions with HeatDial. Unsurprisingly, most of these interactions happened during the heating season, most predominantly in the winter months, while hardly any interactions occurred during the summer months where the heat pumps mostly produce hot utility water. Households C, E, and F had ~150 interactions (Household B had close to 400), with Household E and F participating for the shorter period of the study. Household A ran into technical problems for a couple of months in the second season, but we managed to log ~30 interactions altogether from this household. Household D, G, and H had the lowest number of interactions with ~20 to 40 interactions each. For the households participating for 18 months, Household D had the lowest number of interactions. There were approximately 10 of these interactions per season. From the interaction logs, we also see that half the participants mostly used the HeatDial interface just after getting introduced to the system. A finding in accordance with Yang et al.'s [72] study of the long-term usage of the Nest Thermostat. But more interestingly, the other half kept engaging with the system over longer periods.

In the following sections, we first present findings on how well the system worked in terms of shifting electricity consumption and affecting the comfort of the participants. We then present our three overall themes summarized as convenience, control, and complexity that each illustrates different aspects of how our households perceived and experienced shifting assisted by using the HeatDial system.

4.1 Shifting electricity use and affecting comfort

Based on the data collected on heat pump operation, it was clear that the participants during the study specified temperature tolerance ranges wide enough to make shifting possible. Hence the HeatDial system was able to shift electricity use to cheaper times for the benefit of all participating households throughout the study. On average, the participants specified tolerance ranges between 1.7° and 6.4° and achieved price savings of 6.8% to 16.9% (table 2).

Table 2: Average tolerance settings, preferred temperature, and energy savings obtained.

Household	A	B	C	D	E	F	G	H
Average tolerance range (°C)	5.9°	2.1°	1.7°	3.0°	4.4°	4.2°	6.4°	1.8°
Average preferred temp. (°C)	20.2°	20.4°	19.5°	19.9°	18.6°	19.4°	21.3°	20.9°
Average electricity saving	8.54%	8.25%	10.12%	16.91%	6.24%	9.54%	6.85%	8.50%

One of the notable things from these numbers, however, is that there is not a direct correlation between preferred temperature, tolerance range, and the obtained electricity saving, when compared across households. While one might expect that the highest tolerance range would automatically result in the highest possible saving, reality in the actual households is not as simple as that. The reason for this is that the households are very different, and the obtainable savings from a particular preferred temperature and tolerance range in one household can therefore not be compared directly with another. While for all households, allowing a tolerance range was what enabled the system to obtain savings from shifting electricity use, other factors of each individual household influenced how big this saving ended up being. These were factors such as the level of house insulation, type of heating system (floor heating, radiators), electricity market trends, local weather, and even household routines, such as showering in the morning (affecting the heating of utility water while electricity is usually expensive). These factors all influence the performance of the individual heat pumps differently, so while it is clear that some saving is achieved in all households, the exact saving differs too.

To illustrate how the HeatDial system obtains price savings in an individual household, fig. 5 shows the heat pump data collected from Household E on a single day in April 2016. On this day the tolerance range was set to 18-23° and, the preferred temperature to 19°. From the obtainable price saving data (fig. 5 top), we see that most money can be saved around 5 o'clock in the morning, after which there is a drop (A). At the same time there is a measured drop in temperature in the house, nearing the 18° lower boundary (orange line on fig. 5 bottom).

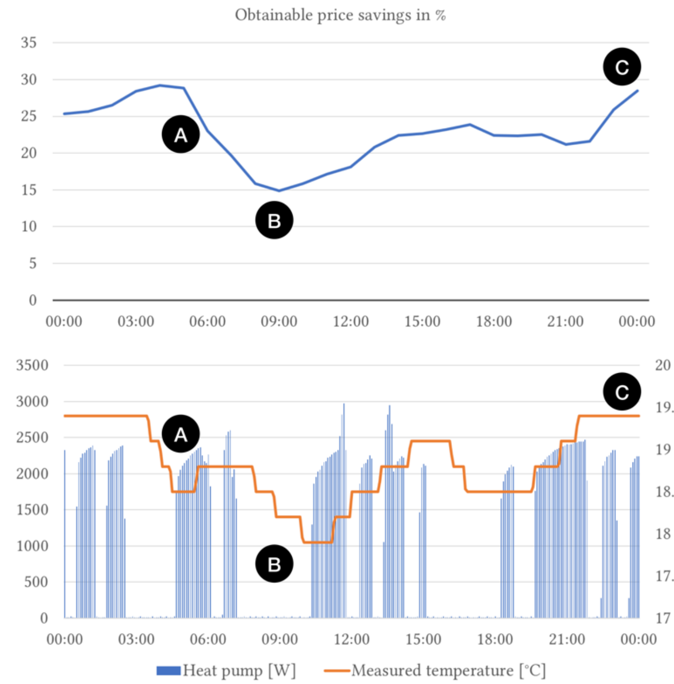


Fig 5: Data collected from Household E over 24 hours on 18 April 2016. The top graph shows the obtainable price savings. The bottom graph shows the measured indoor temperature (orange line), and the electricity consumed by the heat pump (vertical blue bars).

The HeatDial system therefore schedules the heat pump to run at this time, and for a couple of hours (blue vertical bars on fig. 5 bottom). The HeatDial system then schedules the heat pump to go on standby for 3 hours between 7:00 and 10:00 while the price saving is low (B). During this time, the measured temperature in the house again drops close to the 18° lower boundary, triggering the heat pump to run again around 10:00 when the obtainable price saving has increased. As the obtainable price saving peaks upwards after 22:00 (C), the HeatDial system heats the house above the preferred temperature of 19° in order to make use of residual heat in the house the next morning, when the price goes up again.

From the data collected on heat pump operation and measured temperatures in the households, we also get an overview of how the HeatDial system affected the comfort of the participants in terms of indoor temperature fluctuations (see table 3).

Table 3: Average tolerance settings, and fluctuations in measured indoor temperature.

Household	A	B	C	D	E	F	G	H
Average tolerance range (°C)	5.9°	2.1°	1.7°	3.0°	4.4°	4.2°	6.4°	1.8°
Average fluctuations (°C)	1.63°	1.99°	1.48°	1.27°	2.73°	1.4°	2.22°	0.78°
Average fluctuations	8.11%	9.46%	7.68%	6.13%	13.79%	7.16%	10.54%	3.72%

The first observation from this is that no household, at any time, specified a tolerance range of zero (essentially using HeatDial as a standard thermostat). Rather, they allowed tolerances of as much as 6.4° on average over the duration of the study (household G), with 5 of the 8 households (A, D, E, F, G) on average allowing a tolerance of 3 or above. This shows that the fluctuations in temperature, resulting from the

HeatDial system shifting electricity use, did not negatively affect participants' comfort to a degree where they wanted to disable this. While allowing tolerances of up to 6.4°, looking at the measured temperatures in the households, the actual fluctuations were very rarely that large. In fact, temperatures only fluctuated on average between 0.78° and 2.73° (between 3.78% and 13.79%) from the desired temperature specified, with a maximal fluctuation of 8.91° (Household B on 5 June 2016). This shows that even though the HeatDial system was able to obtain notable energy savings, by allowing temperature fluctuations, this did not influence comfort much negatively. This observation is also confirmed by our qualitative findings, and discussed further in relation to the themes of staying in control, and complexity of heating in real life.

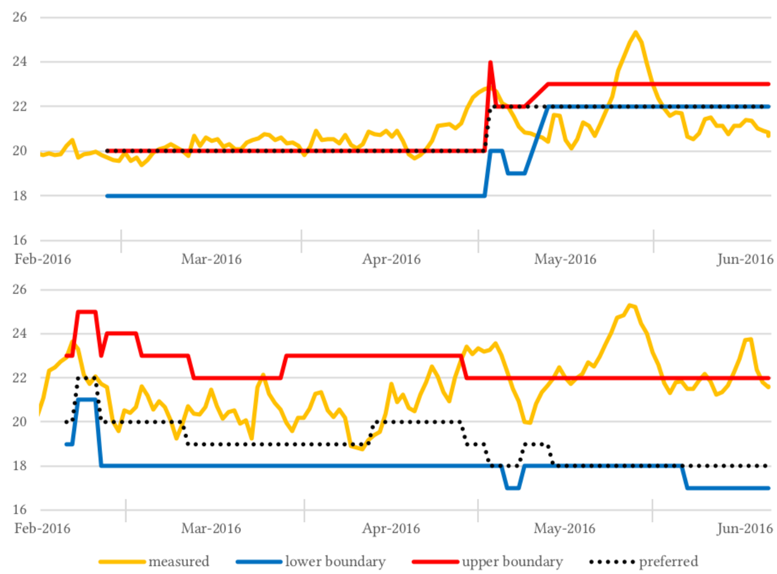


Fig 6: Fluctuations in measured temperatures for Household H (top) and Household E (bottom) in relation to tolerance and preferred temperature settings. The peak in June shows a period of warm weather, where the outside temperature sometimes exceeded the upper boundary set.

As with the energy price savings, the measured temperature fluctuations were not only influenced by the tolerance ranges set in the HeatDial system, but also depended in the characteristics of each individual household. For instance, Household D and Household A recorded minimum fluctuations despite having allowed tolerance ranges of 3-6° on average. In these cases, both households made regular use of additional means of heating in some areas of the house, which of course had some effect on how the HeatDial system could operate. Household A made regular use of a wood burner, and Household D controlled radiators in the bedrooms with thermostats. Nevertheless, Household D was still able to obtain the highest energy saving of all (16.91%). The lowest fluctuations (0.78°) were experienced by Household H (fig. 6 top). In this case, participants had specified a rather small tolerance range (1.8°), and also sometimes made use of a wood burner to keep the temperature in the house at an almost constant comfortable temperature of 20-21°. The largest fluctuations were measured in Household E (fig. 6 bottom), where temperatures fluctuated up to 7.28°, with an average of 2.73°. In this case, the HeatDial system operated primarily through radiators rather than floor heating. This resulted in short response times when heating up the house, leading to larger fluctuations. Hence, as can also be seen from fig. 6, during some of the same months (e.g. February to April) Household H experienced small fluctuations and Household E larger ones, whereas during others (e.g. May to July) both households experienced very similar fluctuations. The latter was caused by generally warmer weather, affecting the indoor temperature as the HeatDial system does not provide cooling.

In the following we shift focus to how HeatDial was experienced and understood by the households, both short and long term, structured by the three themes of convenience, control, and complexity.

4.2 Assisted Shifting as Convenience

Our first theme relates to how the households experienced the automatic features of the HeatDial system that assisted them to shift electricity consumption as convenience. The shifting capability of the HeatDial system was a feature well received by all the households and our findings show that this positive reception mostly came down to an enhanced experience of convenience. There were three main reasons for this. First, all the householders thought that deciding the exact running times of the heat pump was a mundane task to engage in. Second, experiencing the system for a long time resulted in householders becoming confident that the system could automate shifting on their behalf while still making them feel in control of the indoor temperature. Third, by automating the decision-making on how to shift, householders did not need to frequently seek to take action for shifting to part of their heating practices. We present more details of these three aspects of assisted shifting as convenience in the following.

4.2.1 When Shifting is Mundane

Our findings show that all householders perceived heating as something that was already conveniently controlled by the semi-automatic heat pump device. Thus, unsurprisingly, all our households reported that having to find times to shift consumption was a task they would rather avoid having to do by themselves:

> Household F — "I'm very supportive of it – I like to have others running it because I cannot sit and watch prices of electricity. It is much better to let some others do it – this is not something I can keep an eye on all the time."

This feeling of convenience influenced the householders' willingness to allow the HeatDial system to assist with shifting. Other studies [12,33,57] have looked more carefully at the kinds of domestic activities householders are willing to shift. These studies suggest that activities become more shiftable when some of the tasks involved in the activity are already managed by semi-automated technology. An example is the activity of washing, where some tasks have been semi-automated by washing machines. We can verify this but also add to this understanding of shiftable activities. For example, Household D saw a benefit in automating shifting times for heating compared to other semi-automated household activities, like clothes and dishwashing, because heating was not something they engaged with on a daily basis:

> Household D — "I prefer automating the running times for the heat pump. I think it would be something else if it were the dishwasher or the washing machine we had to make run at sensible times. Like starting it at 10 instead of after dinner, because it's something you go and do and grab and handle every day. But heat is not like that - it should just take care of itself."

Most households had the same understanding of shiftable domestic activities. This suggests that people are more willing to be assisted with shifting through technology if they perceive the activity as something: a) that is mundane; b) where some tasks have already been semi or fully automated; or c) that they seldom engage in. This finding is interesting because it suggests that assistive technology can be experienced as a convenient way for households to shift energy-related activities — especially if these activities are considered too mundane to engage with on a daily basis.

4.2.2 Non-Intrusive System Behavior

Along the same lines, we also discovered that convenience was related to not feeling intruded on by the automatic shifting features of the HeatDial system. This aspect was generally related to householders becoming more confident over time that the system was able to conveniently control the indoor temperature. This confidence was more evident in households that were less aware of the technical aspects of how a heat pump normally operates. They started to feel more assured because the heat pump was now controlled by a system or people from the ‘outside’ that were more skilled to optimize when to run it:

> Household E — “Now someone is keeping an eye on it and observing if it is running as it should. And if it doesn’t, then there is probably someone out there who is interested in making it run properly.”

This confidence was strengthened by experiencing the non-intrusive behavior of the system for a long time. Although the participating householders allowed the indoor temperature to be controlled by the HeatDial system for 6 and 18 months, only a few had scattered memories of the system not behaving as they expected. The non-intrusive behavior of the HeatDial system meant that assisted shifting became an integrated part of heating the house, as explained by the wife in Household A where the HeatDial system operated for 18 months:

> Household A — “I now think of it as something that has never existed. It just runs.”

Another aspect of the system’s perceived non-intrusiveness was related to the way shifting was implemented in the HeatDial system. Unlike the Nest [72] or SmartThermo [1] that through machine learning will try and explore users’ needs and constraints of comfort in an effort to reduce or shift consumption, the objective of the HeatDial system was to shift consumption by balancing the temperature within the user-specified tolerance range, using information about the individual houses. This meant that HeatDial's shifting strategy did not necessarily lead to big fluctuations in the indoor temperature, but mostly occurred as small fluctuations in line with the preferred temperature. Consequently, most householders rarely experienced significant variations in the temperature, because the HeatDial system managed to effectively use the information about the individual houses to regulate the temperature in line with the preferred temperature. Yet, not being able to experience these variations meant that some of the households got disengaged from interacting with HeatDial interface over time because they did not experience the effect of changing the temperature boundaries. This was explained by the husband in Household C who during the first six months was very enthusiastic about interacting with the HeatDial system, but after 18 months was less engaged:

> Household C — “When I turn these boundaries – can I then experience some difference? – And I must confess that I cannot [...] But maybe the system has been able to utilize running the heat pump at different times but we still have the same good heat – so it is not something we have felt. Therefore, it is difficult to understand what happens when you set these boundaries.”

Nonetheless, the non-intrusive behavior of the system was the main reason why all participating households kept using the HeatDial system to assist with shifting because it was similar to how a heat pump would normally regulate the temperature. Despite some households believing they did not experience fluctuations when changing the temperature boundaries, none turned off the HeatDial system during the six and 18 months they were living with the system. This indicates that experiencing the non-intrusive behavior over time only strengthened the association of convenience with assisted shifting. This is interesting because, although HeatDial controlled an element central to residential living, the non-intrusive behavior also meant that participants came to trust the system over time, allowing shifting to become part of their daily life.

4.2.3 No Need to Take Action

Our findings also suggest that the feeling of convenience was very much related to how the automatic features of the HeatDial system were designed to shift consumption, and how these features already fitted with established routines and expectations of heating. For a householder to take full advantage of assisted shifting in the HeatDial system require frequent exploration of different settings of the temperature boundaries. However, because the HeatDial system can operate without continuous interaction, householders were not required to change routines to keep the system operating. The HeatDial system would just keep taking care of shifting when settings had been chosen. These automatic features fitted well with already established routines of regulating the temperature in these households. When a household decided on a setting, they expected the system to steer after this without them having to keep monitoring the system. An example of this aspect of convenience was found in Household D. They explored a few different settings when first introduced to the HeatDial system and then quickly decided on boundaries for the tolerance range:

> Household D — "I regulated the settings in the beginning. But we do not like it to get colder than 19°. I think a had the upper boundary at 21° in the beginning and then I moved to 22° later so it could heat those times when the electricity is cheap or it makes sense for the system to run. We can just air out if it gets too hot."

This household did not see the need to regularly change these settings in the 18-month period they participated in the study. They explored a few settings throughout the 18 months, but they always ended up going back to this particular setting. This behavior fits with already established routines of how the households regulated the temperature in their homes, even those not considered very sustainable (overheating and then letting the heat out). Because these householders were not accustomed to changing the temperature on a regular basis, they did not feel the need to start considering this after the introduction of the HeatDial system. While some of this disengagement can be explained by not experiencing any change in the temperature, there is no doubt that the households thought it was convenient not having to concern themselves with shifting and specific running times, especially households with many children:

> Household B — "The more automatic the system is, the easier it is for us."

These findings challenge the mixed design intentions of the HeatDial system. Our findings suggest that the HeatDial's automatic features made it convenient for the householders to shift because the control of the automatic features of the HeatDial system fits well with already established expectations and routines of heating. This interplay between control and domestic routines is also highlighted by Davidoff et al. [21] as an important aspect of households appropriation of automatic assistance. However, our findings also highlight a challenge of balancing the notion of convenience and people's willingness to engage with the system and set user boundaries that will allow the system to optimize the designers' intentions. But perhaps this perceived convenience should be seen as the real success of the system because it did not require householders to take frequent action nor high engagement for the system to continue operating under these user constraints. In light of this, one could imagine adding another level of intelligence to the system that does not require householders to frequently engage with specifying temperature boundaries, but only prompts householders when their engagement is needed.

4.3 Staying in Control

While the automatic nature of the HeatDial system was experienced as an enhanced convenience, our study also found that another aspect of assisted shifting was related to being able to stay in control of how the system operated. This is quite interesting because it adds contrast to the first theme. In the following sections, we explain different aspects of this in more detail.

4.3.1 Shifting as Three Temperatures

Although all households liked having a system that automated shifting for them, our findings also suggest that the households appeared to appreciate being able to define and control boundaries that the system was allowed to operate within. The main aspect of this was the ability to feel in control of the temperature in the house facilitated by the three temperature settings in the HeatDial interface. For example, the wife in Household B did not care about specific running times of the heat pump, but clearly wanted to feel in control of the temperature of the house:

> Wife Household B — "So, if you can somehow move some power to where it is more appropriate, then it is fine with us. As long as it does not destroy the comfort for us!"

This wish to stay in control of the comfort boundaries was evident in all the households. Some described choosing settings in the HeatDial system as a 'shifting contract' between the households and the system. The husband in Household F explained this: *"If you can keep the temperature within the interval that I have accepted, then it makes sense to let the automatic control decide when to supply me with electricity."*

While most householders did not change these boundaries very often, they still used the three temperatures to steer how the HeatDial system ran. This meant they also used the two temperature boundaries to specify a tolerance range. As all households on average specified a tolerance range above 1.7 degrees, the HeatDial system was able to shift consumption in all the households. Interestingly though, over time most ended up with a smaller tolerance range, despite not experiencing any unexpected or uncomfortable fluctuations in the indoor temperature. Household E-G, using the system for six months, had at the end of the study chosen tolerance ranges of 3-6°, while Households A-D, after 18 months, settled on ranges of 2-4°. Most of these households had a larger tolerance range in the first six months of the study but changed to a lower range. When questioned about this, some reported that the tolerance range was chosen randomly due to not being able to experience any consequences of changing settings:

> Household B — "Yes, maybe I could have had a bigger span – I'm in doubt why we ended up with having a span of 3. But we tried different things and did not notice a difference. Even though we allowed it to go down to 18 degrees, we never experienced that it has gone that far down."

Others chose a smaller range as a safety option because maintaining comfort was perceived as being crucial for residential living. This was apparent in some of the homes that did not have a secondary heating source. Household D, for example, disliked choosing a lower boundary far from the preferred temperature because the heat pump could be rather slow to warm if they started to feel uncomfortable. They were more flexible with the upper boundary because it was quicker to amend overheating the house by opening the windows and airing out. Thus, the householders described choosing a low temperature boundary as a risk they were not willing to take because they saw this as a threat to their comfort:

> Household D — "Yes, our [tolerance range] ended up being quite small – I think it would be different we had one more heat source. We have a slow reaction time because of the floor heating, so we had to reduce the range. Otherwise, we risk that someday the temperature will go all the way down."

Another aspect of controlling shifting was a confusion about which energy-conserving strategy [51] the three temperature settings facilitated. Our findings showed that despite an attempt to capture shifting as a tolerance range controllable by a household, this did not intuitively lead to an understanding of shifting:

> Household G — "If the gap is large, then I guess I use less power?... Or that is what I believe happens as I have observed the price will drop if I make the gap bigger. Is that not understood correctly?"

While the householders understood the concept of shifting, most had difficulties distinguishing between reduction and shifting when changing the boundaries of the tolerance range. Whereas it was intuitive that lowering the temperature leads to a decrease in price because they used less electricity, it was less intuitive that decreasing the lower temperature boundary would result in a reduction in price because of shifted electricity use. In fact, long-term use seemed to make householders ignore or forget that the boundaries led to shifting, whereas they did not forget that the HeatDial system was a tool that allowed them to control the comfort in the house. This finding illustrates the importance of communicating the sustainable intentions of the system, so long-term engagement and understanding can be sustained.

4.3.2 Foreseeing the Future

To overcome some of the difficulties of understanding and controlling shifting, we purposely designed the HeatDial interface to include information about the consequences and benefits of assisted shifting through eco-forecasts. Forecasts like these are discussed by Yang et al. [72] as a mean to *"suggest courses of action that align with system goals while allowing users to stay in control"* and are not currently explored in the Nest [72]. While eco-feedback and eco-forecasts show little promise of longitudinal behavior change unless people are already motivated [74], the forecasts for HeatDial were designed to provide transparency into the automatic nature of the HeatDial system. They were also designed to nudge householders to consider different temperature boundaries, by showing them possible cost savings.

Although our findings revealed that the visualizations of forecasted cost and temperature variations data did provide some awareness of the benefits and consequences of having the HeatDial system to assist with shifting, our findings also showed that the visualizations of price over time had little effect on nudging householders to make decisions about changing the tolerance range boundaries. This is interesting because while most householders in the first part of the study [30] stated that price was the most important incentive when having to negotiate comfort, it became clear that over time the price had lesser importance when these householders negotiated a larger tolerance range against comfort. An example was householder C who over the 18 months became less enthusiastic about the importance of the price:

> Household C — "I think about the price because I see a number and it will have an impact on whether the number increases or decreases – but will I consider it?"

The temperature forecast was designed after 12 months based on feedback from the four households participating for 18 months. This element was added to the HeatDial system to help households foresee the influence of household inputs on the HeatDial system's strategy to shift consumption, thus giving them more information to stay in control of the assisted shifting. However, our findings revealed that there was a sense of irrelevance associated with this forecast element and some described it as something you could not be sure would happen. This aspect was explained by the husband in Household A: *"It is a prognosis – and therefore not something you can really count on. A bit like the weather forecast – you can never count on that either".* This meant that most householders were somewhat indifferent to the impact of having forecasted temperature variations in HeatDial. However, few did describe these as a help to foresee consequences of choosing different temperature boundaries, although the short-term forecasts did not fit with how often they regulated the temperatures:

> Household B — "The fear of choosing a lower boundary is waking up in the morning, and it is freezing. Now, in principle, we can foresee this, but it requires that we go in and check this every day."

For most householders, the provided information just confirmed that choosing different settings was a negotiation between comfort and money. Moreover, nothing in the data provided a clear incentive to consider negotiating comfort, and besides, for some householders, the price information was not enough to determine the 'best' setting:

> Household G — "I just don't know what the best setting is. So, I don't really know what to choose. The price is not enough because I would say it is already rather cheap."

These findings confirm similar findings found in other studies on eco-feedback systems, specifically that providing monetary incentives rarely leads to a behavioral change that is maintained [46,64,68]. This underpins the challenge of engaging people with sustainability issues, but also shows that some information can be used to provide transparency of an automated system operating in a complex environment like people's homes.

4.3.3 New Routines

While the forecasting elements did not encourage householders to engage in shifting on a daily basis, our findings, surprisingly, showed that half the householders kept using the HeatDial interface regularly during the six to 18 months of our study. However, we discovered that they were often using the interface for other purposes than regulating the temperature. Prior to getting a heat pump, our households owned heating systems that required dirty and physical labor, such as chopping wood, filling coal and oil into burners. Getting a heat pump and being introduced to the HeatDial system instigated new routines that became more about overseeing the automatic work performed by the HeatDial system:

> Wife Household E — "Well – one could say that you now use your time sitting and checking [HeatDial], but it is not the same hard physical work that we used to have."

> Husband Household E — "I look at it a lot because it has become one of those rituals where you turn on your computer and just take a little peek on the various sites. But it's also a way to keep an eye on whether it really works out there."

This need to oversee the work of the system also established new routines related to interpreting numbers. Only Household D rarely looked at any information because the cost of running the heat pump was: *"clearly stated on the utility bill"* and *"the novelty wore off quite quickly"*. The rest of the householders routinely checked different sources for information in an effort to make their own interpretations on how efficient the HeatDial system ran the heat pump. Half of them also started to collect their own information in monthly and even daily logs (see fig. 7), from different sources including the HeatDial interface, the heat pump itself (see fig. 8), and the 'control-your-heat-pump' website.

This finding is interesting because it tells two stories. First, although the householders perceived assisted shifting as a convenience because they did not have to engage in finding running times for the heat pump, half of them did not see any inconvenience in spending time locating, collecting, and interpreting these numbers. Second, engaging in these numbers seemingly gave these householders a sense of empowerment over the system as explained by Householder C: *"I use these numbers, so I know how much it controls and how hard it controls the heat pump."* Nonetheless, this also meant that in most households, only one person was in charge of choosing settings for the HeatDial system because the control became a matter of who had the interest or competence to understand and interpret these numbers:

> Household D — "I haven't used the system. I don't get turned on by numbers in that way. So, I just let him control it. It will also turn messy if we both start to change settings. That just doesn't work."

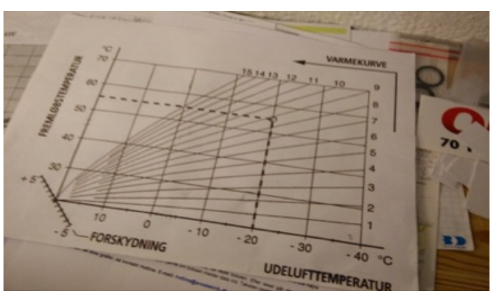


Fig 7: Daily logs of heat pump performance made by one of participating households.

Fig 8: A householder viewing electricity consumption on the heat pump interface.

This is interesting because having to find the 'best' settings clearly left some household members empowered, while others became disengaged. However, our findings suggest that just because one person was in charge of interacting with the HeatDial system, this does not necessarily mean that only one person decides the indoor temperature. In our study, other household members would inform the 'technology responsible' person when they felt uncomfortable, thus 'passively' informing the settings of the system. Categorizing households roles in 'home technology responsible' and 'passive user' when intelligent and automated control moves into the home, correspond well with earlier findings by Mennicken and Huang [43]. Thus, these findings emphasize a need to carefully design interactions for intelligent and automated home technology, so that it becomes accessible and engaging for all members of the household — especially when the entire household is affected by it.

4.3.4 Fooling the System

The last aspect of staying in control is related to how some householders started to 'trick' the HeatDial system to behave in certain ways that could not normally be controlled through the system.

Most of these examples were concerned with how to ensure that there was enough hot utility water for showering. For example, Household B learned over time that the HeatDial system sometimes ran at times that did not guarantee enough hot water on Sunday mornings when they usually bathed their four small children. The husband discovered that if he turned the preferred temperature up high a couple of hours before the planned bath, the heat pump would continue to produce enough water to bath all four children in the household. After a while, the wife found a 'turn off' feature in the HeatDial interface, so she started to deactivate the system on Sunday mornings and activated it again when all the children had their baths. Household D with three teenagers also had a water problem when all family members occasionally had to shower close in time. They tried to overcome this problem by being careful not to use any hot water in the kitchen beforehand.

The husband in Household E experimented with ways to trick the HeatDial system into thinking it was colder than it actually was, to make the heat pump warm the house faster. He did this by placing one of the setup sensors in a cold place, and even experimented with this in different cold places around the house:

> Household E — "If it is really cold in the living room, I sometimes put the [sensor] in the fridge for a while. Or in the hallway, where it is only 16 degrees."

This suggests that although most of these householders with time became conscious of the limitations of the HeatDial system, some of these householders also started, over time, to find creative ways to make the system operate to suit their needs, not always intended by the designers. These findings show there is a need to provide better ways for a household to temporarily influence the behavior of the system, especially when system shortcomings have been experienced over time.

4.4 Complexity of Heating in Real-life.

Extending the above findings, our study also showed that many aspects of the householders' experiences with assisted shifting were more than just how the system operated and how they interacted with it. To capture a more holistic view of experiencing the HeatDial system in residential living, we also report on our participating households' interpretations of comfort, conventions, and the materiality of the individual houses that captures the complexity of shifting heating consumption in a real-life setting.

4.4.1 Comfort

While the households were willing to let an automatic manager shift heat pump consumption to favorable times, comfort was clearly a big concern for all the households. Although the HeatDial interface allowed households to control their boundaries of comfort through the tolerance range, our findings also illustrate that how we label our experiences with an indoor climate, such as 'comfort', is quite complex:

> Household F — "If it is 20 degrees in the living room and perhaps freezing and windy outside, then you might feel quite cold anyway. And this not immediately because of the temperature degree – it is also a feeling – or comfort you can call it."

This suggests that comfort is not an experience only related to a specific temperature. When people try to label this experience, Shove [60] argues that labeling comfort is an individual interpretation of one's body and the immediate physical environment. These types of interpretations were also evident when the householders interacted with HeatDial and experienced specific temperatures as explained by the husband of Household G, *"the temperature has to suit my day to day life, my daily routines, and what I'm currently doing."* These interpretations would also differ between members of the household, leading to discussions about a comfortable indoor climate as explained by the husband of Household E: *"[the wife] is warm-blooded and I'm cold-blooded, so we have some discussions about what a comfortable temperature is".*

Another aspect of comfort was related to context. We found several contextual factors impacting how the householders experienced the comfort of indoor temperature. One of these was the current weather conditions and the variety of the seasons. Some households described that a windy day would make them feel cold, especially if it was the winter season. Others mentioned that the sun shining on a cold winter day might make them feel warm, although the temperature inside stayed the same. Some households also described that their comfort would fluctuate based on what activities the household members were currently engaged in. If they felt uncomfortable, most would use wood burners to make it warmer quickly. Household E was different to the others in this respect. They did have a wood burner but rarely used it. Instead, they would: *"just put on some extra socks and an extra sweater and hide under some blankets."* To help quickly cool down some households would just open windows:

> Household A — "If the sun begins to shine in the middle of winter and it is about zero degrees outside – then all of a sudden it becomes more than comfortable in here... And because it takes a long time to reheat the house after you turned down the temperature, we just air out instead."

HeatDial was rarely used in situations where it was necessary to quickly regulate the temperature. However, some would use the information found in HeatDial interface to help them interpret feeling too warm, too cold, or just comfortable:

> Household G — "Sometimes I feel cold or warm – then I'll check the app. Well, it says it is 21 or 22 degrees. So, I must be feeling cold because I'm coming from outside. Or if you are sitting still you might be feeling cold. Then I might check the app to see what the temperature is – and then it is not that cold anyway."

Our findings illustrate that comfort is something households experience differently due to different factors such as weather condition and activities. Thus, people make different meanings of comfort, which are both personal, and temporal. While the HeatDial system did use information on local weather forecasts, and individuals could capture comfort not just as one temperature but as a range of temperatures, the system did not fully capture the routines people go about to regulate the temperature. Considering this, one could imagine a system that better captures these routines and even challenges the idea that people's established routines are the only actions that can be used to make them feel comfortable, as discussed for example by Strengers [64] and Clear et al. [14,15].

4.4.2 Materiality of the House

Previous studies have reported on how the *physical* characteristics and the layout of a house — materiality of the house — can play a significant role in how people experience and adapt to sustainable technology in their daily routines [12]. Our findings showed that the complexity of experiencing shifting was also associated with the materiality of the house. The physical characteristics and layout of the participant's houses played a major role in the householders' willingness to explore different variations in the indoor temperature within the HeatDial system. One reason for this was that the response time for regulating their houses was slow, because the houses were well insulated and tended to have floor heating in the rooms they occupied the most. On average, it took 24 hours to increase or decrease one-degree of temperature in these houses. If they had experienced this in the past, it made them more conscious of not making the temperature boundaries too large.

> Household D — "I really don't want to play with it, because if we allow it to go down to 16 degrees, we know it will be cold on our feet. It will take a day or two to go down, and another day or two to return."

A few others were less aware of this because the heat was mostly distributed through radiators that regulated the temperature faster than floor heating. An example was household E that did not worry too much about variations in the temperature: *"because our house is quick to warm up"*. As fluctuations in the indoor climate did not worry them, they asked for more ways to regulate the heat during the day to match when they occupied the home.

The layout of the house also influenced how householders understood the controllable temperatures in the HeatDial system. In some households, having just one number represent the preferred temperature did not always correspond with how rooms were used and the layout of the house. Household D, for example, preferred a warm living room and cooler bedrooms:

> Household D — "If you take the entire house – then you have a difference in the desired temperature depending on what room you occupy ... We like it warmer in the living room, less in this [conservatory] room, even less in the kitchen, and not very warm in the bedroom – we are not interested in having 21-22 degrees in the entire house."

To accommodate this, the household installed intelligent thermostats directly on individual radiators in the bedrooms of which they wanted tighter control of. With these thermostats, they could regulate each bedroom differently, meaning that the HeatDial system was not able to work optimally in these rooms because the system knew nothing about these individual settings.

In other households, the three temperature settings were used to find a compromise of temperatures that fitted all the rooms, as explained by Household B: *"we had to adjust the temperature settings, so it matched the temperature we wanted in all the rooms. So, we have the same comfort in all rooms. It required some adjustment in the beginning"*. These findings show that physical elements of the houses played a major role in how householders experienced regulating the temperature, hence their flexibility of allowing a system to fluctuate the temperature within their homes. Together these findings indicate that factors such as physical characteristics and layout of a house played an important part in how assisted shifting was experienced by the householders.

4.4.3 Conventions

Related to the above, our findings showed that experiencing heating through the HeatDial system was very much related to conventions of comfort. Shove argues [60] that the definition of comfort is constantly undergoing new revisions as the conditions for how we understand comfort are changing along with the technology we interact with [60]. New standardizations and conventions for comfort are often specified by the scientific community in an effort to craft better models to control the indoor climate in cooling and heating appliances. A fact also observed by one of our householders:

> Household H — "We have been brought up expecting 20 degrees as the norm [...] I think it comes from the old Danfoss thermostats where it was supposed to be on 3 strokes, which I believe is equivalent to a temperature of 20 degrees. But as we have gotten older we like to have it 21 degrees in the living room."

To some degree standardization and conventions of comfort were also implicitly present through the interactions with HeatDial. HeatDial allows householders to specify temperature boundaries of their comfort through lower and upper-temperatures in one-degree intervals. This design rationale was an effort to make a definition of comfort as concrete as possible, so both people and system could interpret its meaning. While the automatic manager worked well with this rational definition for specifying comfort, our findings showed that the interpretation for a few of the householders was less clear-cut, as explained by Householder E: *"I really don't know what they [the temperature boundaries] mean, but they seem to be something that is needed to be able to control the heat pump".*

However, more interestingly, most of our householders started to talk about comfort being measured in zones after interacting with the HeatDial interface for some time. When regulating the heat, the husband in Household F explained that *"it is the comfort zone that we regulate when it becomes too cold. When we come under the comfort zone of 18 degrees, we must somehow find a way to counterbalance it."*

This is interesting because it shows that after interacting the HeatDial system and specifying ranges of temperatures over time and during different seasons, the participating households also used this convention to understand their indoor climate. This illustrates that households started to change their understanding of comfort and actively use the tolerance range convention to regulate the temperature in the household, instead of the one temperature setting they used before being introduced to the HeatDial system. This indicates that conventions can be designed and hence influence how households experience comfort, introducing new and different ways for intelligent technology to assist householders with shifting.

5 DISCUSSION

Our study has revealed interesting insights into eight householders' use of a prototyped smart grid technology assisting them to shift their electricity consumption to more favorable times. The study showed that households were willing to allow an automatic manager in the HeatDial system to assist with shifting as they perceived this as a convenience. However, our findings also demonstrated that it is not a trivial endeavor to design interactions for assisting households to shift electricity in an understandable and meaningful way.

The aim of this research was to study how householders experienced an eco-manager assisting them to shift electric heat pump consumption long-term. The results of our study clearly showed that the participating householders appreciated both the non-intrusive automatic features in the HeatDial system and being able to control the system boundaries. These two features were the main reasons why assisted shifting became an integrated part of how these householders heated their homes. The design idea of a mixed-initiative system design "where the system pursues the goal of energy savings, and the user is free to pursue their goal of immediate comfort within certain system-defined bounds" is raised by Yang et al. [72] as a way to balance competing objectives. This design strategy was followed in the interaction design of HeatDial, where users could set boundaries of comfort, while the system pursues the goal of shifting a heat pump's running times. However, while our participants appreciated both the automatic and control features in the HeatDial system, our results show that there are still challenges to be addressed in these kinds of mixed-initiative systems. We address these in following sections.

5.1 Missed Opportunities for Acting Sustainable

One of these challenges is how to inform householders to choose the 'best' setting, so an assisting eco-manager can operate within the users' specified boundaries while also optimizing energy conservation strategies, like shifting. To help householders with such choices eco-feedback and eco-forecasts can both provide awareness, as discussed in [28,34], and also be used to close the gap between values and actions, as found in [22,74]. While the eco-forecasted elements in the HeatDial system aimed to provide information to raise awareness of both the benefits and consequences of living with the system, these elements were also designed in an effort to improve the scrutability [32] and accountability [4] of the intelligent HeatDial system operating in a complex environment like peoples' homes. However, our findings showed that providing the 'right' information within the framing of 'smart' technology adds complexity to how such information is understood and experienced in the context of everyday life, also discussed by Norman [45].

In the HeatDial study, the feedback information was designed to frame the interaction as a 'seek and explore' scenario aiming to appeal to the curious heat pump owner. This interaction design did allow these householders to explore and control system boundaries, but it did not fully capture householders heating routines. With this form of interaction, it is expected that a householder is willing to use 24-hour forecasts to explore what would be the 'best' setting by experimenting with different temperature settings. The challenge here is that the information is only available for the next 24 hours, while regulating indoor temperatures is not something these householders do on a daily basis, due to the physical characteristics and layout of their houses. Moreover, this scenario made it difficult for our householders to determine what the 'best' setting was, as they became unsure what effect changing temperature settings would have on their homes long-term. Consequently, these boundaries were sometimes chosen at random or as a safety option fearing a worst-case scenario.

This problem with users understanding the exact effect of interacting with an eco-manager is also reported by Alan et al.'s [1] study of the SmartThermo and Yang et al.'s [72] study of the Nest thermostat. However, unlike both these studies, where users had difficulties understanding how their interactions served the machine learning features for regulating the temperature, the householders in our study had difficulties understanding why their interactions hardly had any effect on their comfort. The main reason for this was because the HeatDial system was efficient in using different sources of information about the individual houses so it could implement a strategy of balancing shifting around the preferred temperature. Using this kind of different individualized information about the house and context rather than trying to derive user preferences meant that shifting hardly ever led to unexpected fluctuations in the temperature.

Furthermore, the expectation of daily engagement, framed in the feedback elements in HeatDial, conflicts with householders' experience of assisted shifting as non-intrusive system behavior. However, it was this attribute of the HeatDial's behavior that led to a feeling of convenience and thus was successful in making shifting part of these households' everyday life. For the householders, this feeling of convenience was built over time, by continuously experiencing the non-intrusive behavior of the system and becoming confident that the system could enact shifting while still attending to their comfort needs. Asking householders to engage daily with the system did not fit convenience because it would interrupt already established routines of how often they regulate their temperature.

5.2 Tension Between Calm Technology and Proactive People

The above observations underpin two challenges that need to be addressed when designing interactions with eco-managers that aim to smartly assist householders to sustainably consume energy namely (1) how can we design eco-managers so they are appropriated into the routines that constitute everyday life in a household, while still ensuring that householders do not miss out on opportunities to engage and retain sustainable settings of an eco-manager? And (2) how can we balance the difference between disengagement in sustainability issues and householders' confidence in allowing an eco-manager to act sustainable on their behalf? We believe that these two questions relate to a broader discussion on the role of designing interactions for ubiquitous computing in everyday life. More specifically, they relate to the tension between, on one hand, Weiser and Brown's vision of calm computing [69] and, on the other hand, Rogers' vision of creating proactive and engaging experiences through computing [55].

This tension was evident in our study of HeatDial and also present in similar studies [17,72]. Thus, we see this tension as relevant for HCI researchers and practitioners engaged in the design of future eco-managers. In our study, assisted shifting became part of the householders' heating routines, as they experienced the HeatDial system as non-intrusive in their everyday life – a quality that fits well with Weiser and Brown's vision of calm technology [69]. However, one can question if this behavior is enough if we want people to retain and engage in shifting or other sustainable practices. While our findings highlight that the HeatDial system successfully automates shifting conveniently, this behavior of the eco-manager also hides awareness of shifting as an environmental challenge that needs to be addressed in the expected future. Designing engaging and proactive experiences is addressed by Rogers [55] who suggests moving beyond the idea of the 'proactive computer' towards supporting 'proactive people'. Rogers envisions ubiquitous technology to "not to do things for people but to engage them more actively in what they currently do" [55]. Because of HeatDial's automatic non-intrusive nature, the presence of the system does not, in itself, change people attitudes or behavior, engage people, or raise questions about sustainable energy consumption. Thus, we believe there is a need to explore how to balance an eco-manager that performs routinized and mundane tasks in cohesion with household members, and the interactive features and information that assist householders in engaging and retaining sustainable energy consumption.

Finding a balance between these visions in the design and development of eco-managers opens up for new interesting directions to be explored. One noteworthy direction could be to explore designs of eco-managers that assist people to be more proactive in their control of the eco-manager. Towards this end, we suggest exploring engaging designs that combine automation with recommendations like those proposed in ThermoCoach [73] or Temperature Calendar [16], where users are given recommended settings for their eco-managers. One could even envision deriving these recommendations using additional smart technology to produce sustainable guidance [25]. In this scenario, proactive suggestions can be sent to households when circumstances change, e.g., energy prices or the local climate, without having to engage users in finding the 'best' setting on a daily basis. However, we need to see how households will appropriate sustainable recommendations served this way long-term, before being able to see if the results are different from when households are presented with conventional eco-feedback [68].

Another interesting direction is to use a more holistic understanding of how energy-consuming routines are performed, challenged and changed through our design interventions. As our findings show, creating a design that has to be adapted into established routines and at the same tries to challenge the meaning of these routines, is complex, because these routines are shaped by the materiality, social norms and other interrelated practices within a household. Therefore, we believe more efforts need to be put into making practices the unit of design [38,52,53,64] when designing, developing, and evaluating eco-managers that aim to change how domestic practices are performed. Towards this direction, we suggest considering the different aspects of practices [61] to better direct the design of eco-managers that aim to both intervene and be appropriated into household routines in an effort to better them as sustainable *co*-managers of everyday practices. However, to take the practice-oriented approach further, an interesting line would be to challenge household routines through eco-managers as explored by Clear et al. [15]. In this direction, designs could either provoke [54] or speculate [9] about practices to proactively engage households to adapt eco-managers as co-managers in everyday life.

5.3 Supporting Social Interactions

While eco-feedback seldom leads to behavior change that is maintained long-term, some studies have shown that eco-feedback can also be viewed as a resource that people can engage with. This engagement can lead to more open discussions and reflection about sustainable practices within the home [68] or within the workplace [16]. However, Hargreaves [29] argues that while the eco-feedback can lead to open discussions about sustainable electricity usage, acting sustainable is often the result of more complex, social negotiations between different members of the household. One reason for this is that individual, specific actions are not isolated incidents but rather a part of a more complex set of cultural and social practices [11]. So while eco-feedback can be argued to be limiting in persuading the individual to change, and perhaps more importantly, maintain this behavior [11,23,52,68], eco-feedback also has a potential for influencing practices because it can open up discussions within the household.

Our findings showed that while HeatDial's eco-forecasted elements rarely led to a discussion of what shifting is, the presence of the HeatDial system did lead to discussions about how assisted shifting could influence the heating in the households. Thus, we found that an assisting eco-manager can provide some of the same properties as eco-feedback. By allowing the HeatDial system to shift, this technology became part of creating an indoor climate experienced by all members of the household. Although we found that it was predominately one person in a household interacting with the HeatDial interface, negotiations about comfort took place amongst the entire household. That family structures play an import role in negotiations about sustainable behavior in the home is also discussed by Barreto et al. [3]. Moreover, as our study show, design and technology take part in shaping people's understanding of, e.g., thermal comfort. However, what is more interesting, is that after the HeatDial system was introduced in our study, our participants started to refer to comfort using the convention of our designed tolerance range, even those household members that did not interact with the HeatDial interface. So instead of just heating their houses after one temperature as they did before, the householders would understand their comfort within boundaries of temperatures after living with the HeatDial system for a while. Some of the participants have even continued to use the HeatDial system after this study has ended because the interaction design of the eco-manager served their needs for specifying comfort.

What we can determine from this is that by experiencing the system long-term, the participants understood and would regulate their heating based on boundaries of the tolerance range – a convention design by us – instead of the one temperature setting they were used to. This just shows that conventions made by designers can influence how households perceive and potentially regulate their indoor climate, opening up new ways for technology to challenge people's perception of, e.g., comfort and convenience.

5.4 Long-Term Studies

In this research, we aimed to study our eco-manager long-term in real-life residential settings having four households involved in our study for 18 months, while four other households participated for six months. We chose to conduct a long-term study to ensure that our households would experience different weather seasons while interacting with the eco-manger. Spring, summer, autumn, and winter are quite different for Danish households in terms of heating. But conducting long-term research studies also have a number of embedded practical limitations as argued by Rogers [56], stating that conducting long-term studies is usually stacked up against the cost of researcher tenure and the fact that "papers must be written and research budgets are tight". In fact, Rogers [56] argues that today's burning question within HCI research is "How long should my study run for?" and she continues by saying that some researchers argue in favor of a few weeks, others say several months, and finally some even stress that more years are needed to demonstrate sustainable and long-term effects. This is also evident if we consider the study duration of papers in our related work section. For example, in the Tariff Agent project, they ran two separate but related studies where the first study ran for two weeks, and the other study ran for six weeks [2], while the FORE-Watch study was seven months long [35], and finally the SINAIS study was more than one year long, with 20 households [48]. However, Rogers' question on how long a study should run still remains unanswered.

Our long-term study enabled us to observe how our participants interacted, experienced, and adapted to an eco-manager over an extended period of time. While there can be issues of deploying such technology into homes, as described by Pereira et al. [48], we do believe we need time to observe how households adapt to such technology after the initial excitement has settled, to supplement existing knowledge about the potential such technologies have to solve sustainable problems. As both our study and Yang et al.'s [70–72] Nest study show, when residential life takes center stage, it can be difficult to motivate householders to engage and negotiate comfort. But as we argued through our findings, the real success of the HeatDial system is that the system kept being used long-term by all our householders. They kept using the tolerance range in the HeatDial interface to specify comfort and although they may not have regulated these as often as it is necessary to take full advantage of the shifting, experiencing the non-intrusive behavior of the system meant that shifting became and remained a part of these householders' lives.

6 CONCLUSION

In this paper, we have reported from a study of a prototyped smart grid technology, HeatDial, deployed with eight households for a duration of six and 18 months. HeatDial is designed to assist householders in shifting electricity consumption of their electric heat pumps. Through the HeatDial system, householders can specify temperature boundaries while letting an automatic manager handle the shifting of heat pump operation to more sustainably favorable times. HeatDial also provides feedback in the form of 24-hour eco-forecasts so that householders can foresee the consequences and benefits of allowing the automatic manager to enact shifting within their user-specified boundaries. From shifting electricity use, HeatDial was able to facilitate price savings of 6.8% to 16.9% While doing this, average fluctuations in measured temperatures were still kept between 0.78° and 2.73° on average, and comfort thus largely maintained.

Through our study, we found that the HeatDial system three themes, summarized as *convenience*, *control*, and *complexity*, each illustrating how the eight households interacted, experienced, and adapted to the HeatDial system assisting them to shift heat pump consumption over time. We found that householders were happy to let an eco-manager shift heat pump consumption, as they were not interested in engaging with such mundane activities on a daily basis. Because HeatDial was able to enact shifting in a non-intrusive way, assisted shifting became part of these householders everyday heating practices long-term. However, our findings also suggest that although our HeatDial system was a convenient tool for controlling shifting, willingness to challenge temperature boundaries was often influenced by the complexity of heating practices, mainly influenced by the materiality of the house, weather season, and understandings and meanings of comfort. These findings have broadened our understanding of how eco-managers can assist with shifting electricity consumption for heating. However, for smart interactive technology and eco-managers to reach their full potential of supporting domestic householders to act sustainably in their daily routines, there are different still issues that need to be addressed by HCI researchers and practitioners.

1) In designing the functionality and information representations of eco-managers, HCI practitioners should look closely at the diversity of household roles and structures, and through their designs attempt to accommodate for these. Sustainability solutions, such as eco-managers, are often designed for the person in the household who is 'responsible for the home technology'. However, to engage other 'passive' members of the household, who are perhaps less technology-engaged, eco-managers may need to cater for other roles and needs in the household. 2) In designing interactions for eco-managers, HCI practitioners should explore different balances between calm technology interactions, and interactions that support people in being proactive. Striking such balance is important for supporting households in doing their everyday practices in a more sustainable way through eco-managers, while at the same time feeling in control of their eco-manager. 3) In broadening our view of what eco-managers might do, and what they might look like, HCI researchers should prototype designs that are deliberately different from what we have already seen, and study them in real life, before integrating ideas into commercial products and infrastructures. 4) In studying eco-managers in use, HCI researchers should increase focus on the long-term implications of design interventions, to better understand what shapes the use these technologies in everyday life, and account for the effects and complexities associated with prolonged use of them in residential settings.

Based on our experiences of conducting the HeatDial study, and also confirmed by recent work in sustainable HCI [24,39,52,53,67], sustainable interaction design stands at a crossroads between informing design by looking towards more practice-oriented methods or continuing to look for ways to improve our designs that are not connected to a particular time and space. Thus, one of the biggest challenges facing HCI researchers and practitioners of smart grid technologies for residential settings is in making these sustainability interventions, sustainable themselves.

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