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User engagement with smart home technology for enabling building energy flexibility in a district heating system

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Abstract. The future low-carbon emission societies rely on energy systems bearing an increasing share of renewable energy sources (RES). Consequently, demand-side management and energy flexibility become a key solution to compensate for the intermittent nature of RES. District heating systems hold a large potential for energy flexibility if households are actively integrated. While previous research and local policies have applied demand-side management such as smart meters, new smart home technology envisions full employment of the flexibility potential of the building stock. Morning energy demand peak is a major concern for district heating systems in Nordic countries. Demand-side management for district heating has thus mainly focused on morning hours peak-shaving. While integrating smart home technology as a demand-side management solution, the household becomes a flexible energy hub for thermal energy storage. While the technical potential of achieving such flexibility has been investigated, less research has been carried out concerning how users engage with smart home technology and how this influences the possibilities for load-shifting of the indoor space-heating demand. By conducting qualitative studies (interviews and 'show and tell' home tours) in 16 Danish households, this paper explores how users engage with smart home technology and how this influences the possibilities for load-shifting in a district heating system. The study provides insight into how the occupants interact with different smart technologies providing space-heating control. Results show that engagement with smart home technology must be understood as part of people's everyday practices. The flexibility in energy demand must be generated by understanding and changing practices to make them more flexible during peak hours. While smart home technology holds the potential for adding flexibility within the district heating system, the technology is rarely used as intended by occupants. Smart home technology is disrupting, and users rapidly create workarounds in order to perform everyday practices. Load-shifting during morning hours is thus a technical possibility, but the dominant techno-economic paradigm embedded in smart home technologies remains a barrier, as the latter must adapt to the everyday practices.

1. Introduction

Traditionally, the building stock is perceived as a passive end-user within the energy grids. Because the building stock accounts for one-third of the final energy usage and CO_2 emissions globally, large efforts during these last decades were dedicated to drastically improve the energy efficiency of buildings [1]. Although this is a major target to achieve sustainability of future societies, there is a paradigm shift concerning the role of buildings in the energy grids. In the context of Smart Energy Grid systems [2], the building stock should be considered as an important active element which can help to reduce the

mismatch between instantaneous energy production and usage by means of energy load-shifting, peak-shaving and valley filling. These demand-side management methods are commonly called "building energy flexibility" strategies [3]. Activated by a penalty signal (energy spot price, CO2 intensity of current energy production, local state of the grid, marginal production cost, etc.), this building energy flexibility can significantly ease the establishment of a reliable and sustainable energy supply network with massive penetration of intermittent renewable energy sources (RES). Moreover, it can solve local or global congestion issues occurring at critical periods in the bottleneck weak points of a grid.
The recent studies on the topic have investigated the potential of buildings providing flexibility services to the grid by smart control of thermal and electrical energy loads. Electricity which is produced locally (for example with photovoltaic panels) or imported from the grid, can be stored in the building's batteries [4] or in the electrical vehicles connected to it [5]. Furthermore, the building stock has a large potential for thermal storage in hot water tanks (heating system and/or domestic hot water tank) [6] and in the indoor environment thermal mass [7]. The latter can be used as a cost-effective thermal storage solution when employing indoor temperature setpoint modulation [8]. Excess RES production can thus be stored in the built environment and allows significant space-heating energy shifting over few hours for poorly insulated buildings, and up to more than 24 hours for well-insulated buildings with large effective thermal inertia without jeopardizing the thermal comfort [9].
These demand-side management and building energy flexibility strategies are based on advanced control systems, enabling a certain communication between the Smart Grid, the building systems and the occupants. In practice, the activation of the building energy flexibility is performed by so-called "smart home technologies". These technologies also insure occupants' comfort and awareness about the status of their building. However, there is a clear lack of understanding whether these smart home technologies will be largely accepted by households, how they will interact with the it and whether occupants will allow control signals from the outside (penalty signals from the grid, energy providers and distributors) to interfere with their own private indoor environment. The households' perspective is a key topic of investigations, as it can be a strong barrier to the successful implementation of energy flexibility measures. The study presented in this article is part of the transdisciplinary InterHUB project. The InterHUB project aims at understanding the interactions between the different actors and stakeholders of the building energy flexibility in a smart energy grid system [10]. The current paper focusses on assessing the engagement of occupants in dwellings with smart home technology for enabling building energy flexibility in Denmark. Following the details of the methodology and the different study cases, the preliminary results of this ongoing investigation are presented. The authors hope that this study can give a clearer insight into user's acceptability to other researchers working on the topic. The article closes with the main conclusions and suggestions for future work.

2. Methodology

The overall methodological approach is qualitative in design. Semi-structured interviews and home tours have been conducted in 16 households of the Copenhagen urban area (Denmark). Applying an open character, the interviews aims at understanding the 'doings and sayings' of the occupants, and thus assess how occupants engage with smart home technologies. As space-heating is largely considered 'invisible' by occupants [11], special attention has been put on everyday activities and routines performed by the occupants. This has given valuable insights into how space-heating practices are re-configured when the smart home technologies are integrated within the domestic sphere. Prior to the interview, a semi-structured interview guide has been drafted. The interview guide consists of themes concerning space-heating, comfort and engagement with smart home technology. The interview guide is structured so that the interviewee can 'pursue' reflections occurring during the interview. Each interview had a duration of 1 ½ to 2 hours. During the interview, the occupants were asked to give a home tour, explaining their use of each room in the house. This approach is valuable for generating insight into mundane everyday activities such as adjusting space-heating or airing, which might not have been clear if the interview was staged otherwise. Furthermore, occupants were asked to 'show and tell' how they operated their smart home technologies. This often led to a conversation about their general experiences with technology. The methodological approach is largely in line with the research conducted on energy consumption in the domestic sphere [12,13,14,15,16]. Such methodology highlights the complexity of everyday life and underlines the fact that research on user engagement with technological equipment and energy consumption must be a user-centric approach. The approach relies on an epistemological assumption that, in order to generate knowledge on user engagement, research must examine how occupants themselves perceive their own practices. While other studies have looked into user engagement with smart home technologies and their potential benefits (including the possibility for energy savings [17]), only a few of them have assumed that everyday life practices are the smallest unit of analysis and that any research enquiry must, therefore, uncover it [18]. Qualitative methods are thus preferred as they are able to capture the complexity and unpredictability of everyday life. Following Bent Flyvbjerg [19], the use of case studies has also been valued as a fruitful way of both generating insight and hypothesis for further investigations, but also testing such hypothesis and contributing to theory building. As this short paper only presents preliminary results, the focus is placed on the trends of user engagement with smart home technology for enabling space-heating flexibility. Consequently, this article acts as a starting point for further analysis of user engagement with such technologies.

3. Study cases

The current analysis incorporates four different study cases [20]. Each study case represents a residential area (varying in size) which applies the same smart home technology for enabling energy flexibility. Four interviews were conducted in each study case and all present adult family members (18+) were involved. While some interviews were conducted with only one person, the others involved multiple people and, thereby, captured the negotiation of everyday life between household members. Furthermore, small kids were also present at some of the interviews, but they were not interviewed. However, their presence unfolded the engagement and practices of kids, and how the adult members of the household reacted to them (e.g. keeping a higher floor heating temperature so that the kids could play on the floor). The selection of the households was made to gain a broad representation of different households, varying in terms of size, age of occupants, educational background and gender. As shown in Table 1, the interviews include a 50/50 gender variation, a wide age distribution (21-58 year old) and variation in terms of household size (1-5 occupants). However, the data is slightly biased in terms of the occupational background of the informants. Indeed, the vast majority of the interviews has senior-level jobs. This is with the exception of students who were represented in 1/3 of the interviews. In all study cases, the energy for indoor space-heating and domestic hot water production is supplied by a district heating network. The study cases are either apartments or terrace houses and are all recently built with a good level of building envelope thermal performance. A short description of each study case can be found in the following sections.

3.1. Måneparken, Trekroner, Roskilde: Måneparken was constructed in 2004 and located in Trekroner, in close proximity to higher education institutions and 30 km from Copenhagen. The estate consists of 31 apartments: 24 one-bedroom apartments (35 m^2) and 7 two-bedroom apartments (39 m^2). The apartment block consists of two floors, with apartments on each level. The rents range from 500 to 800 euros per month. The estate is a student residence administered by the local social housing organization. The apartments are thus only occupied by students. Most of them are in their early twenties. The allocation of the apartments is based on a waiting list, meaning that the occupants represent different social spheres of the society. Most occupants live in the apartments for short time periods (½ - 5 years). Most apartments are only occupied by one person. The seven two-bedroom apartments accommodate small families or flatmates living together. Within the apartments, radiators are installed in the kitchen/entrance and the bedroom(s). In the bathroom, floor-heating is installed. Control of space-heating is enabled by two different types of devices. Digital thermostats (Danfoss Living Connect©) are placed on every radiator, allowing the occupant to adjust setpoints directly on each of them. The thermostats are connected to a central Danfoss CC link© In-Home-Display (IHD) located in the kitchen. The occupants can control all thermostats and set rules or schedules for the entire apartment space-heating. Different sensors in the house can be used for the control rules, e.g. opening windows automatically shuts the space-heating off until the window is closed again. The thermostats and the IHD are also accessible to the occupants via an application installed on their smartphone, allowing the remote management of the space-heating. Besides the Danfoss technology, a model predictive control (MPC) system called LeanHeat© is in use. By measuring both indoor (occupancy and consumer profiles) and outdoor conditions (temperature and humidity), the system optimizes the heat flow going into the apartment.

Table 1. Overview of the study cases.

Name and location	Building	People	Technology	Interview details
Måneparken Trekroner Roskilde	31 apartments 1 and 2 bedrooms Built in 2004	Social housing for students. Mostly single living tenants, the rent is 500 - 800 euros per month. Few apartments with couples.	District heating. Radiators in rooms, floor heating in the bathroom. Control by Danfoss CC Link© and Leanheat© technology.	4 interviews: 1 male and 3 females. Occupants: 1-2 Age: 21-25 All students
Frikvarteret, Nordhavn, Copenhagen	29 terrace houses 100 - 200 m^2 Built in 2016	Ownership – prices start at 800,000 euros. Mostly families from upper-middle-class. Also couples.	District heating. Floor heating in all rooms. Control by digital on-wall thermostats, and fuel-shift controlled by the utility.	4 interviews: 4 males and 3 females. Occupants: 2-5 Age: 35-58 Senior-level jobs
Sundmolehusene Nordhavn Copenhagen	72 apartments and 11 terrace houses 45 - 210 m^2 Low-energy building Built in 2017	Ownership – prices from 270,000 euros to over 1 million euros. Differentiated household composition, but mainly upper-middle-class and upper-class.	District heating. Floor heating in all rooms. Control by digital on-wall thermostats and external control (centralized) during a limited time period.	4 interviews: 3 males and 3 females. Occupants: 2-4 Age: 21- 58 Senior-level jobs and 2 students.
Havnekanten Nordhavn Copenhagen	86 apartments 55 - 146 m^2 Low-energy building Built in 2016	Ownership – prices from 300.000 to 1.4 million euros. Differentiated household composition, but mostly families from upper-middle-upper class.	District heating. Floor heating in every room. Control by Danfoss CC link© system with the possible scheduling. Sensors in the whole apartment.	4 interviews: 3 males and 2 females. Occupants: 1-4 Age: 35-56 Senior-level jobs.

3.2. Frikvarteret, Nordhavn, Copenhagen: Frikvarteret is a newly built (2016) residential area, in the recently redeveloped area of Nordhavn. Nordhavn is located nearby Copenhagen city center. Since the beginning of the 2010s, the Nordhavn district has undergone an extensive transformation, from being an old harbour area to an attractive residential and business area. The prices in Frikvarteret starts at approximately 800,000 euros. Frikvarteret was one of the first residential complexes of Nordhavn and consists of 29 single-family terrace houses, ranging from 100 to 200 m^2. The terrace houses are in 2 - 3 floors and rather spacious for Danish standards. The occupants are, to a large extent, middle-class to upper-class families, typically with small children. An under-floor heating system is installed in all rooms of all houses. A hot water tank with an electric heating unit has been installed. It allows "fuel-shifting" by selecting either district heating network and electricity as heat source. Control of when to conduct fuel-shift is made by the district heating company. Occupants can control and monitor space-heating by using digital on-wall thermostats. They also have access to a web-based platform to visualize their energy consumption related to space-heating on a day-to-day basis.

3.3. Sundmolehusene, Nordhavn, Copenhagen: The Sundmolehusene was built in 2017, and consists of 72 apartments and 11 terrace houses. The size of the apartments ranges from 45 to 210 m^2. The building block is considered as a low-energy building with energy for heating (indoor space and hot water) and ventilation below 20 kWh/m^2 per year. The prices for apartments in Sundmolehusene range from 270,000 to over 1 million euros. In general, Sundmolehusene is intended for upper-middle-class. Occupant composition varies significantly, consisting of both families, couples and single-person households. An under-floor heating system is installed in all rooms of all dwellings. Control of space-heating is performed by digital on-wall thermostats. Information about the humidity level and CO_2 concentration are also displayed. On-wall thermostats are placed in every room. Opening of the doors and windows are monitored to automatically shut heating off. In 10 of the apartments, enabling flexible heating demand has been experimented. The space-heating of those dwellings was, for a short period, controlled from the outside by researchers from the Technical University of Denmark [21].

3.4. Havnekanten, Nordhavn, Copenhagen: Havnekanten, constructed in 2016, is also located in Nordhavn. The estate consists of 86 apartments, ranging from 55 to 146 m^2. They are considered low-energy buildings with minimum space-heating needs and good indoor comfort. Like most of the housings in Nordhavn, the price for Havnekanten dwellings range from 300,000 to 1.4 million euros. This makes Havnekanten one of the most expensive areas in Nordhavn. Consequently, its occupants are mostly people from the upper-middle and upper class. The different apartment sizes in Havnekanten induce a differentiated household composition, and both families, couples and people living alone reside in the apartments. Floor heating is installed in every room of all the apartments. Additionally, temperature sensors are installed throughout the apartment, in order to evaluate the possibilities for enabling heat storage in the building. Control of space-heating is performed by a decentralized system: Danfoss CC link©. Within the apartment, digital on-wall thermostats are placed in every room, allowing the occupants to adjust indoor temperature setpoints. In addition, users can centrally monitor, control and schedule the space-heating from the IHD. Sensors detect if doors or windows are opened, and automatically turn off space-heating. Space-heating can also be controlled and monitored remotely, using a smartphone application.

4. Results and discussion

As previously mentioned, this paper only presents the preliminary results and trends observed during the qualitative studies in four different cases. Overall, the interviews showed that the young informants were more satisfied with the technology compared to the older informants. Despite educational background or familiarity with technology or the energy system, older informants were generally more concerned about the functionality and accuracy of the technology. In terms of household composition, larger households had a more diverse engagement with the technology (e.g. different settings in different rooms or more frequently shifting setpoints). This was often the results of continuous negotiations between the household members. That being said, there was a clear trend towards males being the main user of the technology. They were responsible for the setup and the continuous operation (also in terms of technological failures).
In general, three main trends for user engagement with smart home technology for enabling a flexible space-heating demand have been observed:

- The importance of embodied know-how
- The notions of comfort evolve
- The smart home technologies as scripted material arrangements

4.1. The importance of embodied know-how:
Throughout the 16 qualitative interviews and home tours, one trend which stood out was the importance of the so-called embodied know-how. It appeared that informants who were very familiar with the use of smartphones and other network-connected technologies had greater ease for controlling smart home technologies, and hence they engaged more actively and continuously with the systems. This was especially evident among the young occupants who approached the technologies with confidence and quickly made use of the advanced features of the system. It was also this group of users who expressed the largest satisfaction and interest in the system. As one occupant expressed: *"Yes, but it is also because it is easier. (...) On an ordinary radiator, what the hell does "5" mean? Does it mean 50 °C, does it mean 5 °C, what does 5 mean, what does the number 5 mean? I have no idea what that means. So I do not know if I should put it on 3 to get the temperature I want or if I should put it on 5, so I have never*

figured out what the number means in terms of degrees. Wherewith Danfoss, I know exactly that it is 20 °C if I set it (The system) *to 20 °C. So it is much easier to control now"* (Occupant A3).

On the contrary, occupants who had less experience with 'smart' technologies, expressed less interest and sometimes had dissatisfaction with the system. These occupants were generally more uncertain of whether or not the system operated correctly and performed different experiments to test it. Such experiments often included material arrangements and tools which the occupants trusted and were familiar with, such as thermometers: *"Yes, I bought it* (a thermometer) *because I just had to see if it said the same thing. I think I bought it because the problem with the heat control in the bathroom didn't really work, so I brought it there to investigate what the temperature really was"* (Occupants E3).

Other occupants felt a disempowerment by the smart home technology, resulting in rare or no engagement with the systems. The former thus adapted other practices for achieving their desired level of comfort, such as putting on blankets or wearing more clothes. These results emphasize the importance of occupants' prior experience with similar technologies. This is often an embodied experience in which previous hand-on experience is more important than e.g. the user having read information about the technology. The results highlight the fact that competency comes in different forms and that tacit knowledge is important for enabling user engagement with smart home technologies and thus the possibilities for enabling a flexible heating demand. While occupants with embodied competencies related to these technologies might be more competent practitioners in order to provide flexibility within the current system, these results also highlight that future systems have to incorporate how users without such embodied knowledge can contribute to flexibility. One solution might be an increased automation and less user control.

4.2. The notions of comfort evolve

A second trend was the tendency to increased notions of comfort, as smart home technologies were integrated within the household. This result has also been found in other studies e.g. [22]. It appears that, as smart home technologies offer the occupants a convenient way of controlling space-heating, this is often translated into an increased notion of comfort. Several occupants thus expressed that their indoor comfort requirements had increased, since moving into a house with smart home technologies. This often resulted in higher indoor temperature setpoints, equivalent to a comfort level for which being able to walk barefoot within the household was pleasant. This was clearly evident in households which had floor heating installed. Occupants liked the notion of warm feet, and quickly adapted to this as a notion of comfort throughout the house by considering that being able to walk barefoot in the entire house was now a normal level of comfort for them. One expressed this sensory notion as follows: *"It (the temperature) is somewhere between 22 - 23 °C. I think it is the most comfortable. I like that you can walk around without having to wear a big sweater or that you can basically walk around in socks or barefoot"* (Occupant C2).

Similar investigations have previously highlighted the sensory feelings that floor heating generates among occupants, and how this tends to be translated into increased notions of comfort [14]. However, such findings are not directly connected to the engagement with smart home technology, but are evident in low-energy buildings in general. The smart home technologies and the remote control were generally well perceived by the occupants, who were largely positive towards the increased automation of the domestic sphere. They were mostly valued because of their ability to increase the convenience of controlling space-heating. In relation to generating flexibility for the district heating system (e.g. peak-shaving), the occupants were generally more sceptical about enabling such feature themselves. They preferred that this was done either automatically (MPC, Machine Learning) or centrally by a third party such as the utility or the building manager. However, occupants expressed that such control must not decrease comfort within the dwelling. This was furthermore challenged by the other space-heating practices which occupants seemed to have. Most of them were e.g. used to opening windows for a variety of reasons. In general, a cold bedroom was preferred during the night, and opening windows in the morning and throughout the day was considered a healthy practice. This can be problematic for enabling space-heating flexibility and using the indoor environment for heat storage. For instance, one informant expressed his practice of airing the bedroom while keeping the floor-heating turned on as follows: *"I like the feeling that there is a bit of heat in the room, while there is fresh airing"* (Occupants C2).

4.3. The smart home technologies as scripted materials

As well emphasized in the scientific literature, technologies are scripted towards a certain use. Through a careful design process, developers hope that they will be used as intended. However, literature shows that material arrangements (equipment) are not always used as intended. This was also evident throughout the 16 interviews and home tours. Most noticeably, the differentiated use and engagement with smart home technologies and understandings of how it worked. This stresses the importance of careful design and implementation of smart home technologies for enabling a flexible space-heating demand, considering the differences in engagement. One clear trend was that while the technology scripted a certain use, occupants often created workarounds, as the technology interfered with other practices in their everyday life. Such workarounds included moving the IHD to other locations within the household (away from the front door), resulting in a decreased engagement with the system. Others did not like the LED lighting that the smart home technologies produced, and thus turned the whole system off. The technologies were also used very differently than their intended script, and some occupants used IHD as a wall-clock or a simple thermometer.

The use of smart home technology was also often scripted by the occupants themselves, and engagement with it varied from being used as a simple on/off device to a precise scheduling tool. Occupants often negotiated between the script of the smart home technology and that of other material arrangements in the household. Occupants did not perceive the technology as flexible as it was initially scripted, and felt that it did not operate fully with the other home materiality. For instance, the occupants of low-energy dwellings did not perceive floor heating as flexible, as it would take too long to heat up if turned off. Consequently, they felt that the smart home technologies were not compatible with such purpose.

5. Preliminary conclusions

In future low-carbon societies, domestic energy consumption must be more flexible, as energy will increasingly have to rely on intermittent energy sources such as wind and solar power. While energy consumption within the domestic sphere is rather mundane, as occupants perform everyday practices (e.g. getting ready for work and school in the morning), peak-demand problems are increasing. The possibilities for time-shifting such peaks have recently received important interest. In that regard, smart home technologies have often been highlighted as the possible mean for enabling energy flexibility by use of heat storage in the indoor environment and its thermal mass. However, there is a clear need for deeper knowledge concerning the smart home technologies acceptability by the households, how the latter interact with the smart home technologies and if they will allow external control signal to alter their private indoor environment. This paper presents preliminary conclusions from an ongoing study on occupant engagement with smart home technologies in 16 Danish households. By applying qualitative methods, i.e. in-depth interviews and home tours with occupants, the results highlight three trends of occupant engagement. First, the importance of embodied knowledge, showing that occupants who have previous and hands-on experience with same or similar technologies increasingly engage with smart home technologies and take advantage of the more complex features. These occupants are also generally more positive about the system and more competent at enabling flexibility. Second, a trend of increasing notions of comfort is evident. As smart home technology provides the occupants with a more convenient way of controlling space-heating, such convenience is often translated into higher comfort norms such as higher indoor temperature setpoint, challenging the potential for increasing flexibility in the system. Third, although technology is often scripted towards a certain use, i.e. enabling flexibility, they are often not used by the occupants as intended. Engagement with smart home technologies proved to be very diverse and ranged from taking advantage of the complex features to merely being used as a wall clock or simply hidden away. This research project will continue until the spring of 2021, and during that period the sample size will be increased. The focus will be on broadening the variety of occupants and buildings included in this investigation.

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