A Mixed-Method Approach to Understand Energy-Related Occupant Behavior and Everyday Practices in Multi-Story Residential Buildings

Andersen, Kamilla Heimar; Hansen, Anders Rhiger; Marszal-Pomianowska, Anna; Knudsen, Henrik N.; Leiria, Daniel; Heiselberg, Per Kvols

Publication date:
2024

Document Version
Early version, also known as pre-print

A Mixed-Method Approach to Understand Energy-Related Occupant Behavior and Everyday Practices in Multi-Story Residential Buildings

Kamilla Heimar Andersen[1, 2, *], Anders Rhiger Hansen[1], Anna Marzsal-Pomianowska[1], Henrik N. Knudsen[1], Daniel Leiria[1] & Per Kvols Heiselberg[1]

[1] *Aalborg University, Department of The Built Environment, Thomas Manns Vej 23, DK-9220 Aalborg Ø, Denmark*
[2] *SINTEF Community, Department of Architectural Engineering, Børrestuveien 3, 0373 Oslo, Norway*
* *Corresponding author: kahean@build.aau.dk, +47 400 79 398*

Abstract

In recent decades, attention has increased to investigating energy-related occupant behavior and everyday practices to contribute to bridging buildings' well-known energy performance gap. Understanding some of the mechanisms behind this gap, such as, the energy-related decisions and/or shared heating practices among occupants, could foster effective strategies for promoting energy efficiency. However, such mechanisms are not yet well identified, especially in residential contexts and low-energy buildings, where the relative impact of occupants' behavior is predominant. Aiming to contribute to tackling this knowledge gap, this article presents the results of a sequential mixed-method approach, combining quantitative and qualitative methods to study the energy-related practices of six occupants in five households of a multi-story low-energy household block located in Denmark. The households are monitored with sensors measuring heating use, room temperature, and heating setpoint temperature, enabling to capture human-building interactions at a high resolution. The quantitative analyses showed substantial differences in heating behavior and practices and thermal comfort preferences across households and over the seasons (from 90 to 301 heating days a year). Nevertheless, the qualitative study indicates shared practices regarding the use of the feedback display installed in each dwelling (writing down in a diary every day). This suggests that despite individual differences in preferences and habits, households living in the same building still share heating practices, which might relate to interpersonal trust. The findings underpin the importance of collective support and trust in improving feedback implementation and ensuring heating practices to support building energy efficiency.

Keywords

Occupant behavior; Heating practices; Human-building interaction; Heating use; Residential building; Energy efficiency; Thermal comfort; Indoor environment; Energy feedback

Acronym and corresponding Definition

Abbreviation	Definition
AHU	Air Handling Unit
CAV	Constant Air Ventilation
DMI	Danish Meteorological Institute
EROB	Energy-Related Occupant Behavior
GSHP	Ground Source Heat Pump
HDD	Heating Degree Days
HVAC	Heating Ventilation Air Conditioning
KPI	Key Performance Indicator
OC KPIs	Occupant-Centric Key Performance Indicator
OB	Occupant Behavior

PV	Photo Voltaic
REST API	Representational State Transfer Application Programming Interface
RMSE	Root Mean Squared Error
SATO	Self Assessment Towards Optimization of Building Energy

Highlights

1. Uses a sequential mixed-method approach to study heating behavior and practices in low-energy households.
2. The quantitative analysis shows that heating seasons are individual for each household.
3. The qualitative analysis revealed that shared heating practices can foster energy efficiency.
4. Heating practices and behavior are driven by care, compassion and compromise and has fostered a community.
5. Underpins the importance of collective support for successful feedback implementation.

List of Tables

List of Figures

Contents

1. Introduction

1.1 Motivations

In recent decades, the impact of occupants' behavior on residential heating use has received increased attention [1,2]. Occupant behavior encompasses a wide range of everyday activities related to heating and cooling, lighting usage, and appliance usage, which includes adjusting thermostat settings, opening/closing windows, dimming/switching lights, pulling up/down blinds, and turning on/off Heating Ventilation Air Conditioning (HVAC) systems [3,4]. The importance of occupant behavior is justified by much empirical evidence. For example, occupant activities are estimated to explain half of the variation in heating use over time [5], and significant energy savings can probably be achieved by improving occupant energy awareness [6]. This emphasizes the potential benefits of improving energy efficiency, sufficiency, and demand flexibility by better understanding how people impact energy use, for example, to better explain differences between predicted and actual energy use in residential buildings (the so-called performance gap) [7–9].

1.2. A glance at two approaches to understanding occupant behavior

The interest in the role of occupant behavior has a long history within building science. Exemplified by the classic studies of Sonderegger in the late 70s [10] and Lutzenhiser in the early 90s [11,12], two positions have existed side by side for decades: the social/cultural (human) and the technical (material) perspectives on occupant behavior. Research on occupant behavior can typically be divided into two broad approaches. First, technical-empirical studies often focus on *which* indicators of occupant behavior empirically correlate with energy use and indoor climate measures [1–3,6]. Second, socio-empirical studies often focus on *why* occupants use energy (the way they do), *what* energy is for [13,14], and *how* household energy demand is also shaped by everyday activities that are not directly linked to the use of energy [13].

Table 1 presents a summary of the two approaches in occupant behavior literature.

Table 1: Summary of two approaches in occupant behavior literature.

Research preferences	Technical-empirical approach	Socio-empirical approach
Focus	Technical aspects of a system	Socio-technical context of practices
Data	Objective measures	Subjective variables
Methods	Typically, experiments or simulation	Typically, interviews or surveys.
Results	Empirical correlations and explanatory factors (what correlates?)	Interpretation (why do people do as they do?)

Summarized in Table 1, the technical-empirical approach focuses on the technical aspects of a system and emphasizes empirical data and quantitative analysis to understand and solve issues. The emphasis is on measurable, observable phenomena and often relies on experimentation, data collection, and statistical analysis. This approach aims to improve the accuracy of the prediction of building energy demands [15]. To do so, studies investigate *which* measures of occupant behavior correlate empirically with objective measures of energy and indoor climate, resulting in many explanatory factors that relate to occupant behavior [1–3,6,16]. The work by Wagner et al., 2018 [17] exemplifies this by outlining a range of contextual factors that correlate with measures of energy use and indoor climate and dividing contextual factors into physical environmental factors, such as building qualities, psychological factors; knowledge, preferences, and lifestyles, social factors; group interaction and social status, and physiological factors; age, sex, and health status.

Although the study includes factors like knowledge, preferences, and social status, it diverges from the socio-empirical approach by not interpreting these within its context.

In contrast, the socio-empirical approach considers a system's social and technical aspects as interconnected and co-dependent. It argues that technical solutions must account for their social context, including the human actors, their relationships, and the societal norms. The essential questions become *why* occupants use energy (the way they do) and *what* energy is for [13,14]. This includes studies of the meanings for understanding why households perform heating practices the way they do, for example, related to expectations of comfort, cleanliness, and convenience [18–24], but also studies that emphasize the shared and collective aspects of household heating practices, for example, through shared infrastructure [25], social norms [26], and collaborative engagement [27]. The socio-empirical approach also emphasizes the role of interpersonal relations, such as family relations [28,29], and energy habits formed by previous experience [30].

This article combines the technical-empirical and socio-empirical perspectives, using an explanatory sequential mixed design [31], where the qualitative analysis follows the quantitative to expand and provide further nuances to the findings in the quantitative analysis. This is to understand better the complexity of the role of occupants, viewed broadly as human-building interactions influencing energy use and indoor environment. By doing so, the study is inspired by other studies applying a mixed-methods design [14,32–35], and both perspectives are needed in research about occupant behavior [36].

1.3 Aim and contribution of the study

Despite the growing interest in energy-related occupant behavior, there seem to be two apparent research gaps that this article seeks to address.

First, studies tend to take 1) a *technical-empirical* approach, focusing on objective measures, such as temperature preferences or appliance usage by analyzing quantitative data, and 2) a *socio-cultural* approach, focusing on understanding mechanisms of social practices using qualitative methods to analyze subjective indicators, such as perceived comfort, expectations, and care. Therefore, this study investigates occupant behavior using a mixed-methods approach, starting with a quantitative analysis using *objective* measures, such as energy use, and setpoint adjustments, to reveal aspects that might be hidden in nonconscious daily activities, and followed by a qualitative analysis of *subjective* data, related to comfort expectations and social norms, to illustrate the considerations and motivations behind these energy-related activities.

Second, multi-story residential buildings are less commonly used as cases or objects of investigation of occupant behavior, but this study follows an apartment building (in total 24 households) where five out of six households in the same staircase agreed to participate. This enables investigation of the role of interaction with neighbors. Also, the article explores how various households share heating practices. Addressing these research gaps is essential for advancing our knowledge, developing evidence-based approaches, and encouraging energy-efficient occupant practices in buildings, contributing to the future design and operation of buildings.

The following research question guides this study: *What are the main factors that affect the energy-related occupant behavior, specifically heating habits, in a low-energy multi-story residential building, and how do these factors contribute to energy efficiency?*

The article continues as follows: Section 2 details the methods and materials, such as the study case and the qualitative and quantitative content. Section 3 describes the quantitative heating analyses and outlines the occupant narratives. Section 4 consists of the discussion on the key findings while Section 5 presents the conclusion and suggestion for future studies.

2. Methods and materials

2.1 Study case

The case study is a multi-story residential building located in the urban northern region of Denmark. Originally erected in 1949/50, this building underwent significant renovations in 2012/2013 to a low-energy building with an energy label A2020, which in Denmark complies with the requirements of building class 2020 in the Danish Building Regulations of 2018 [37,38]. Situated in a semi-sheltered area, the building is surrounded mainly by residential buildings of similar or lesser height. The building has five staircases, each having either three or six apartments, a total of 24 apartments in the block (see also [39]). This study case investigates the left staircase (red rectangle in Figure 1) with six households.

The heating demand is fully covered by a brine-to-water Ground Source Heat Pump (GSHP), installed in dedicated technical rooms. This GSHP generates Domestic Hot Water (DHW) and supplies hot water for the underfloor water-based heating system. The DHW tank and the energy storage tank are both located in the same room as the GSHP. Figure 1 shows the south façade of the study case and corresponding staircases.

Figure 1: The South façade of the case study where the red rectangles are the approximate locations of the GSHP in separate technical rooms.

The heating control of the GSHP is managed through an outdoor temperature-compensated curve, which adjusts the water's supply temperature based on the outdoor temperature (measured right outside the residential building). Although all households receive a similar supply temperature to the zones, the flow rate of the water varies depending on the setpoint temperature managed by the occupants.

Figure 2 shows the placement of the heating setpoint thermostat in households to the left and to the right. The occupants can modulate the heating setpoint thermostat by rolling the thermostat from 1 (inducing a lower mass flow resulting in lower indoor temperatures) to 7 (inducing a higher mass flow resulting in higher indoor temperatures). Households to the right have a total heated floor year of 55 square meters, and the households to the left have 72 square meters.

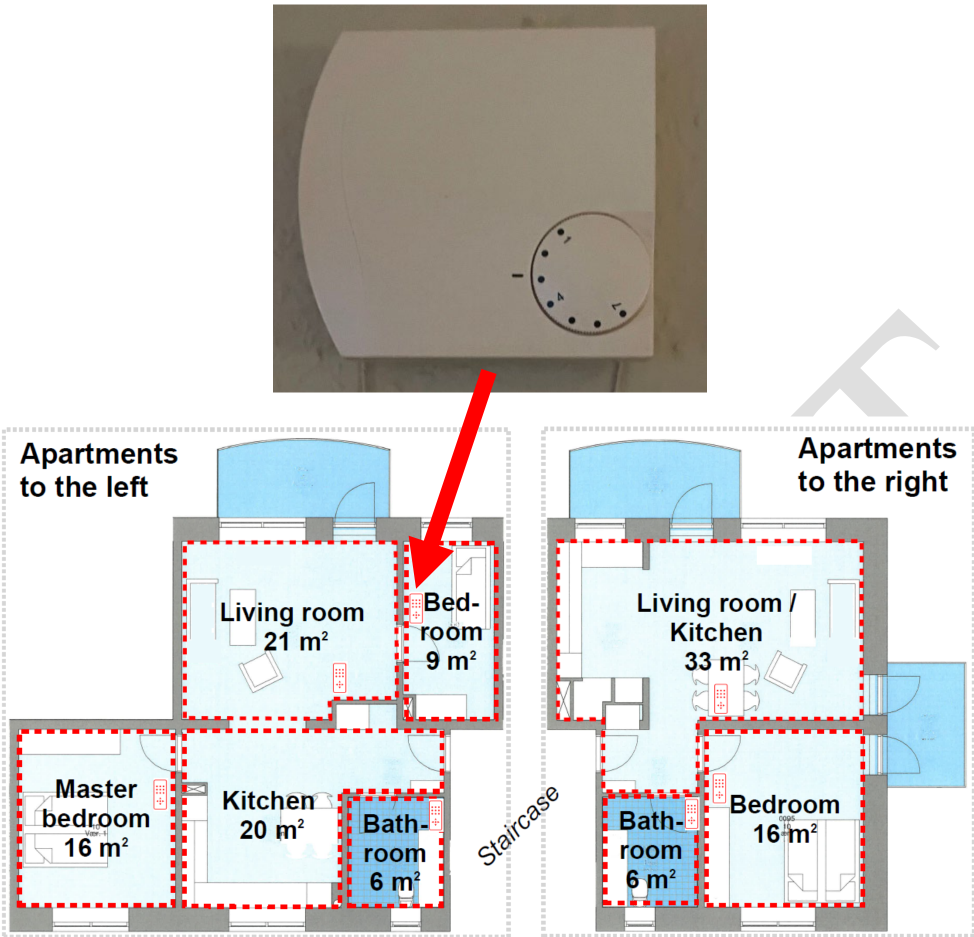
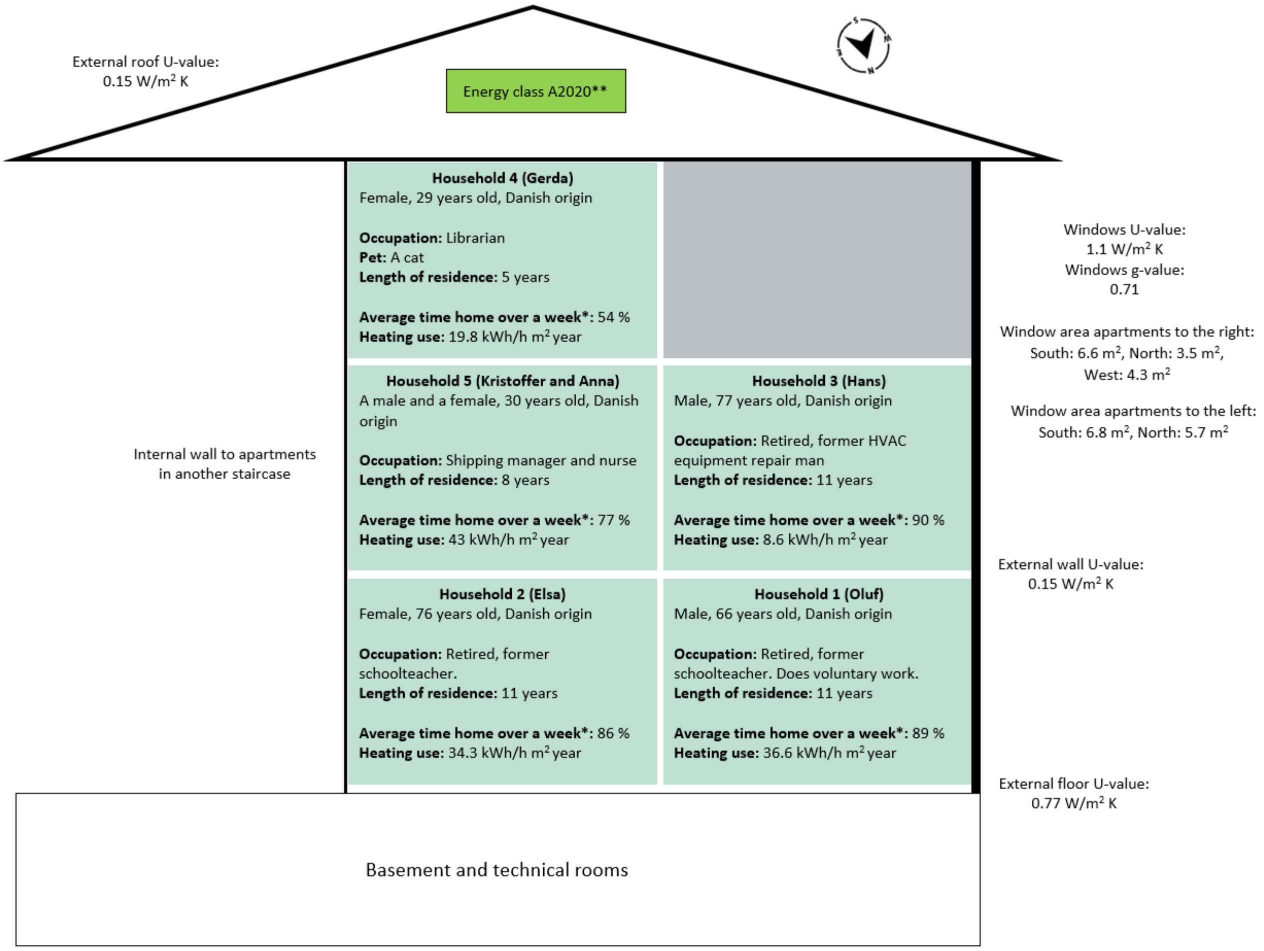


Figure 2: Placement of the heating setpoint thermostat in households to the left and to the right.

Each household has a decentralized Air Handling Unit (AHU) located at the entrance that supplies balanced Constant Air Ventilation (CAV) in the bedroom and living room. The exhausts are placed in the kitchen and bathroom. Additionally, the building is equipped with approximately 200 square meters of photovoltaic (PV) panels on the roof. These panels supply about 60% of the electricity used by the 24 households and directly power the GSHP.

Figure 3 outlines the description of the case study building characteristics and the occupants. The heating use is measured from 19.01.2022 to 19.01.2023. The occupants are anonymized and given fictive names, shown in parenthesis in the figure.



*Average time home over a week: From a survey [40].

** Calculated according to Danish regulations [37,38].

Figure 3: The description of the case study and the occupants.

In each household, a feedback display was installed at the entrance of each apartment as part of the comprehensive renovations undertaken in 2013 (See Figure 4). This display shows the household's water, heating and electricity use, and average relative humidity. The occupants can see the use they had yesterday, the last week, and year-to-date data for the abovementioned parameters. Since utility usage varies per household, monthly energy bills differ, affecting the individual "Aconto" or advance payment. This data is visually represented through three smiley face icons indicating satisfaction levels, ranging from a frown (indicating high usage) to a smile (low usage) compared to each household's use, using this "Aconto" as a baseline. When electricity costs are lower due to the onsite PV production, the electricity usage icon is shown with sunglasses, signaling an opportune time to use power-intensive appliances like dishwashers and washing machines.

The housing association that owns and runs this case study's daily operations and maintenance has a strong focus on energy savings and sustainability. The feedback displays are now installed in this housing association's new and renovated households to provide better energy use information and eliminate the end-of-year 'billing surprises' for occupants.

Figure 4 shows two pictures of the feedback display from one of the households.

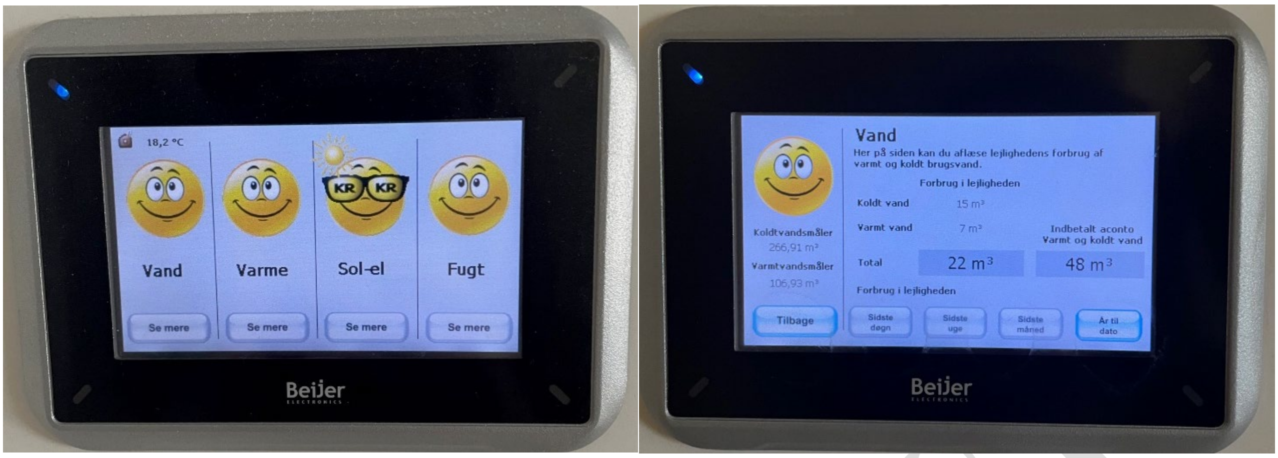


Figure 4: The existing feedback display. The picture to the left shows "Vand": Water, "Varme": Heating, "Sol-el": Smiley shown with sunglasses indicate that it is currently cheap to use electrical appliances, and "Fugt": Relative humidity. The picture to the right shows a more detailed use of the "Vand": Water parameters, such as cold water, hot water, total use, the cold and hot water meter reading, time resolution, and the Aconto paid.

2.2 A sequential mixed-methods approach

The mixed methods approach in this study allows for a more in-depth analysis of the complexity and multidimensionality of energy-related occupant behavior by allowing for a greater range of views on a particular topic [41]. The quantitative data analysis provides insights into quantifiable outcomes like energy use patterns, setpoint modulations, and room temperature. However, such quantitative analysis alone may overlook important subjective factors, motivations, and contextual nuances influencing occupant practices. This is where qualitative data, for example, through interviews and observations, becomes useful. Qualitative methods enable a deeper understanding of the underlying values, perceptions, social norms, and experiences that shape heating practices [34]. Such a triangulation of methods can add rigor and depth to an analysis and strengthen the conclusions drawn from the study [41].

2.2.1 Quantitative data

This study incorporates quantitative data collected from various parameters at household and room levels, covering the period from 19th January 2022 to 19th January 2023. Specifically, the dataset includes for each household:

- Household level:
  - Heating power (kW) (logged as 'instantaneous' values every 5-minutes)
- Room level:
  - Room temperature (°C) (logged as 'instantaneous' values every 15-minutes)
  - Setpoint temperature for heating (°C) (logged as 'instantaneous' values every 5-minutes)

The characteristics, calibration procedure and location of the sensors in the households measuring room temperature, heating setpoint temperature can be seen in a dedicated technical report [42]. The data was retrieved from the case study's database via a dedicated REST API. Subsequent steps involved cleaning the data, checking for and addressing missing data, resampling and interpolating data as needed. Finally, the dataset was processed to aggregate (sum of daily or average daily heating use where applicable) the measurements and convert power (kW) readings into energy use (kWh/h or kWh/day) where applicable.

The outdoor air temperature data is downloaded from the Danish Meteorological Institute (DMI) open API [43], from the nearest available station (06032 Stenhøj).

2.2.2 Qualitative data

The qualitative data used for this study primarily consists of transcriptions and recordings from semi-structured interviews with six occupants from five households. One household did not want to participate. These households were selected based on their location within the same staircase. This particular staircase of the building was targeted for research by the housing association as part of the H2020 SATO project [44], due to the size of the energy system in the building's basement, which makes it one of the largest within the block (two different HP sizes).

The semi-structured interviews were conducted over two weeks during January and February 2023, with approximately three visits to each household (interview, observations, photographs, and field notes). The authors developed and designed an interview guide to investigate occupant behavior concerning room temperature and interest in feedback on reducing energy used for heating, especially in low-energy buildings (after renovation). The interview guide can be found in a dedicated GitHub repository [45]. The interview guide consists of 5 parts with around 3-7 questions, in total up to 35 questions. The semi-structured interviews (hereon known as *"interviews"*) were recorded, and notes were written down during the interview. The first author conducted all the interviews with the households. The interviews were conducted onsite in Danish in each household. Subsequently, the recorded interviews were transcribed in NVivo and Microsoft Word to identify core themes and patterns within the data. In addition to the interviews, field notes were conducted to capture non-verbal aspects to understand better the context and setting of the occupants' practices. For example, photographs were taken during the household visits, serving as visual documentation of energy-related practices, such as manual tracking of energy use.

3. Results

3.1. Analyses of heating behavior in households using quantitative data

This section presents the results from the quantitative analyses of occupant behavior, including setpoint temperature and measured room temperature.

3.1.1 Measured room temperature and heating setpoint temperature

Figure 5 shows room temperature duration curves of the measured room temperature for the different rooms during the whole year from January 2022 to 2023. The figures are arranged according to their physical locations within the building (See Figure 3). As one can observe, the room temperature is the highest in the living room/kitchen for all households except household 1. This is consistent with both the 1) solar gains on the South-facing façade and 2) the higher heating setpoint temperatures in this room compared to the other rooms (except the bathroom, see Figure 6). In contrast, the bedroom has one of the lowest room temperatures, which is consistent with the north-facing façade and lower heating setpoint temperatures (see Figure 6). The bathroom has the second-highest temperatures, probably consistent with the higher heating setpoints and actions such as showers and/or closed internal doors to conserve heat gains. Also, having the internal doors open to rooms with a lower heating setpoint may unintentionally heat those rooms, thus contributing to a higher temperature. The office room type is only located in the households to the left and is typically used as a storage and/or office in these households. Here, the heating setpoint temperatures are generally low (see Figure 6), and occupancy is lower than in the other rooms [40]. However, as this room type also faces the South orientation, the temperature fluctuations are likely due to the solar gains. The living room/kitchen measurements in household 4 are due to missing data from September 2022 due to a frozen sensor.

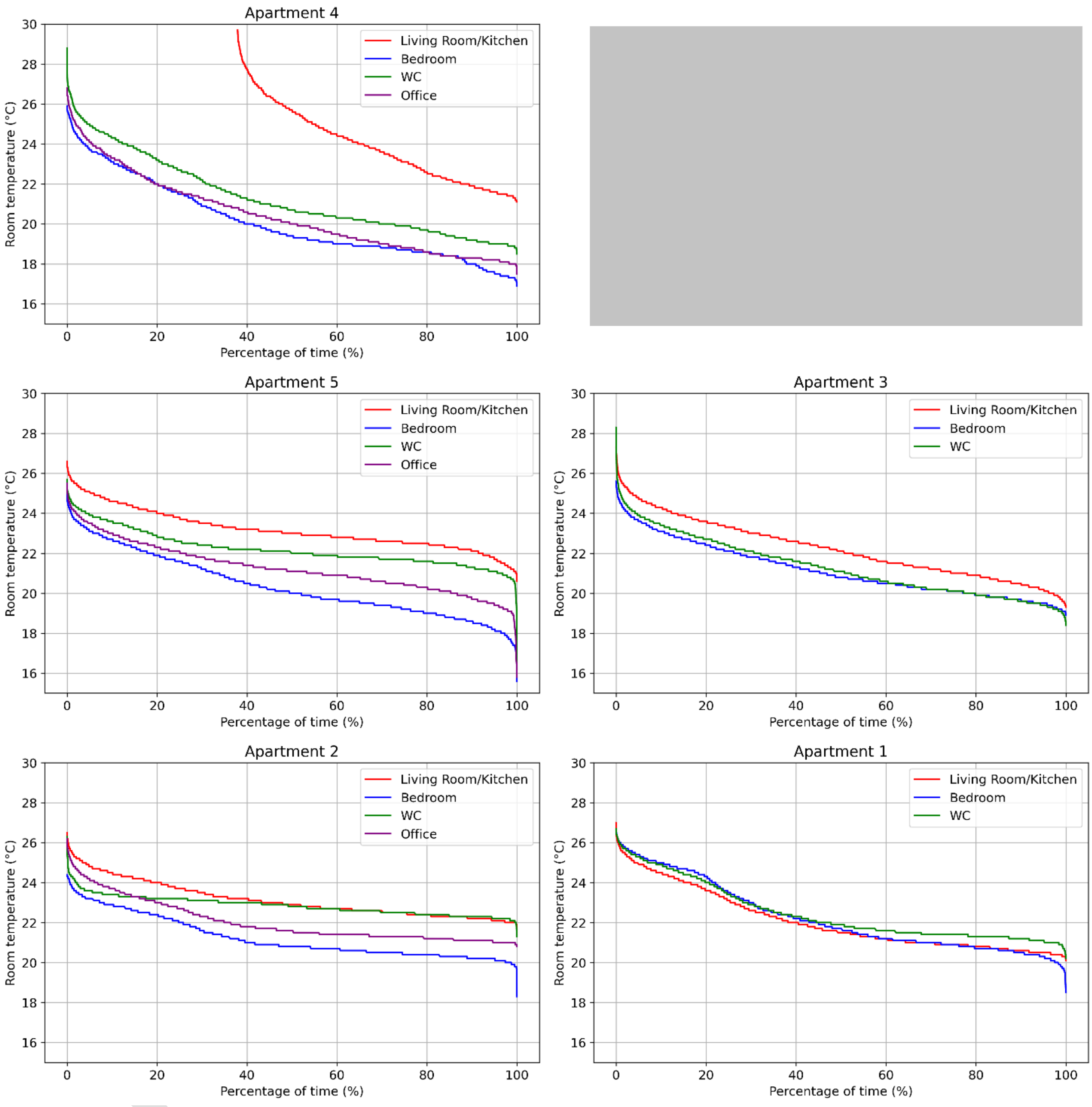


Figure 5: Duration curve of the measured room temperature in each room of each household (19.01.2022 – 19.01.2023).

Figure 6 presents an overview of the temperature setpoint modulations during a year across various household rooms on the primary axis and the daily average outdoor temperature on the secondary axis. The figures are arranged according to their physical locations within the building (See Figure 3).

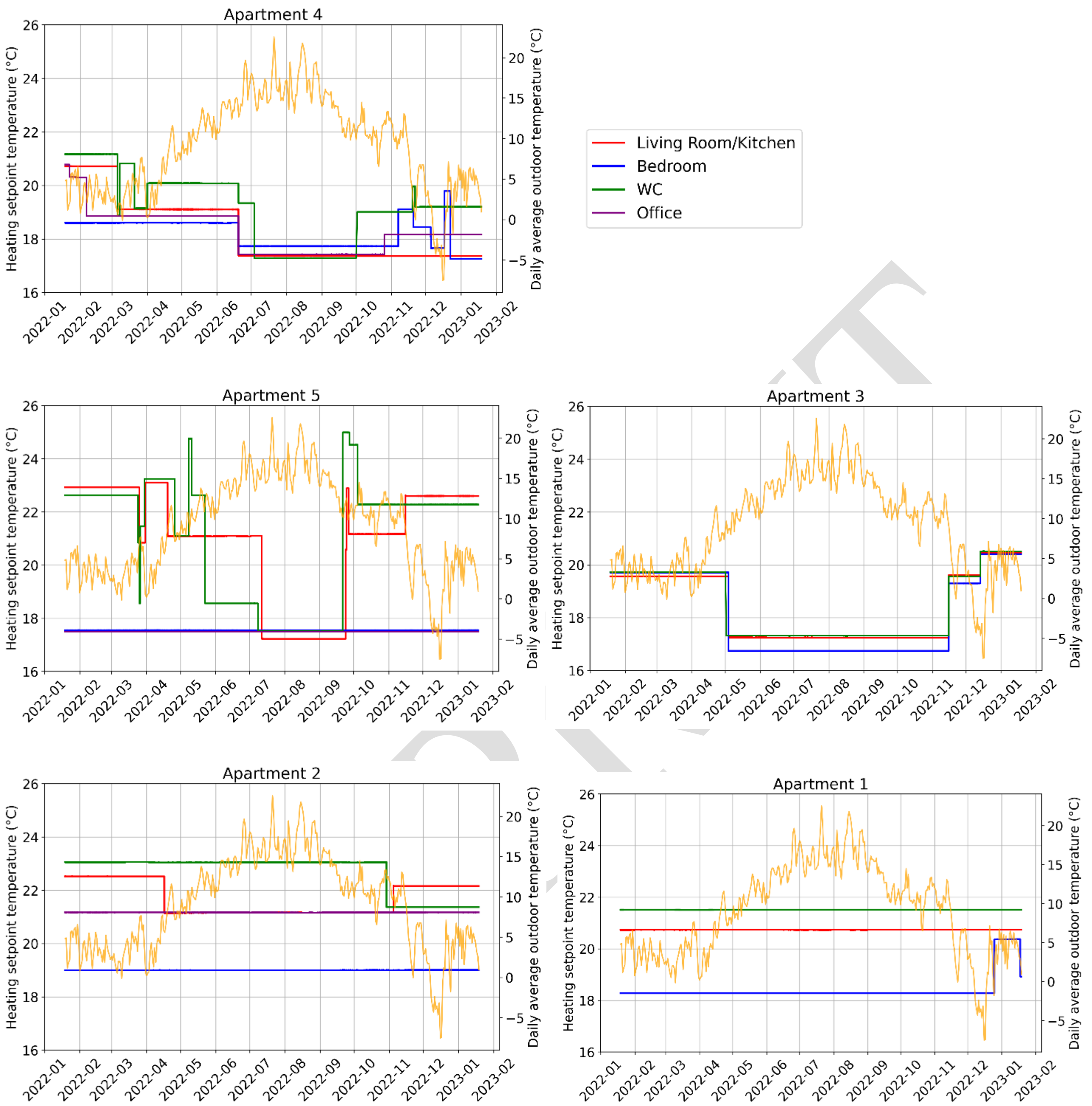


Figure 6: Overview of the human-building interaction (temperature setpoint changes) for each household corresponding to their rooms (19.01.2022 – 19.01.2023).

Notably, households 4 and 5 have the highest frequency of heating setpoint temperature modulations, with 21 modulations per year, suggesting a dynamic approach to thermal comfort management. In contrast, households 1 and 2 have minimal interactions, with just two and three modulations, respectively, which could indicate a more stable heating preference throughout the year. The bathrooms have the most frequent setpoint modulations, possibly due to a typical desire for warmer bathrooms [46]. In contrast, bedrooms maintain the lowest average setpoints, aligning with typical preferences for cooler temperatures during sleep from an occidental perspective [47].

3.1.2 Heating use overview

Five traditional Key Performance Indicators (KPIs) for heating use are presented in Table 2. As one can observe from the computation of the KPIs, there is a large variation between the households. From a normalized perspective, the highest consuming household to the lowest, 2.39 kWh/m^2 per year, differ (KPI 3).

Table 2: Traditional KPIs for heating use computed for each household.

KPI / Household / Occupant	Household 1 / Oluf	Household 2 / Elsa	Household 3 / Hans	Household 4 / Gerda	Household 5 / Anna & Kristoffer
KPI 1: Total heating use 2022/2023 (kWh/year)	2003	2391	496	1365	2557
KPI 2: Monthly heating use (kWh/month)	167	199	41	114	213
KPI 3: Monthly heating use per m^2 (kWh/m^2 per month)	2.32	2.77	0.57	1.58	2.96
KPI 4: Monthly heating use per m^2 normalized by daily HDD (kWh/m^2 per month per HDD)	0.27	0.36	0.06	0.30	0.13
KPI 5: Heating days (heating use > 1 kWh/per day)	195	301	90	148	237

Table 3 indicates the proportion of time during the specified period that the room temperature in each room was higher than the desired heating setpoint.

Table 3: Percentage of time the heating setpoint temperature is below the room temperature (heating is requested) during 19.01.2022 – 19.01.2023.

Household	Living room / Kitchen	Bedroom	Office	Bathroom
1	14 %	2 %	-	36 %
2	12 %	0 %	15 %	45 %
3	2 %	12 %	-	20 %
4	20 %	11 %	12 %	28 %
5	19 %	1 %	1 %	62 %

Figure 7 shows the heating use across different households, distinguishing between heating days (heating use higher than 1 kWh per day, marked in red) and non-heating days (heating use lower than 1 kWh per day, marked in gray). Heating is activated based on the heating setpoint temperatures controlled individually by occupants in each room. Specifically, heating is supplied when the current room temperature is below the setpoint, and conversely, no heating is supplied when the room temperature is above the setpoint.

As one can observe, households 3 and 4 have the lowest heating days throughout this year. In contrast, household 2 shows a higher frequency of heating days, including atypical heating months such as June, July, and August. This pattern suggests that the occupant's personal comfort preferences influence the heating uses. Additionally, the impact of solar gains, particularly on the south-facing façade, becomes noticeable starting in March, when the sun's higher altitude leads to more direct sunlight entering through the windows. This solar effect likely contributes to the reduced heating use in the spring months.

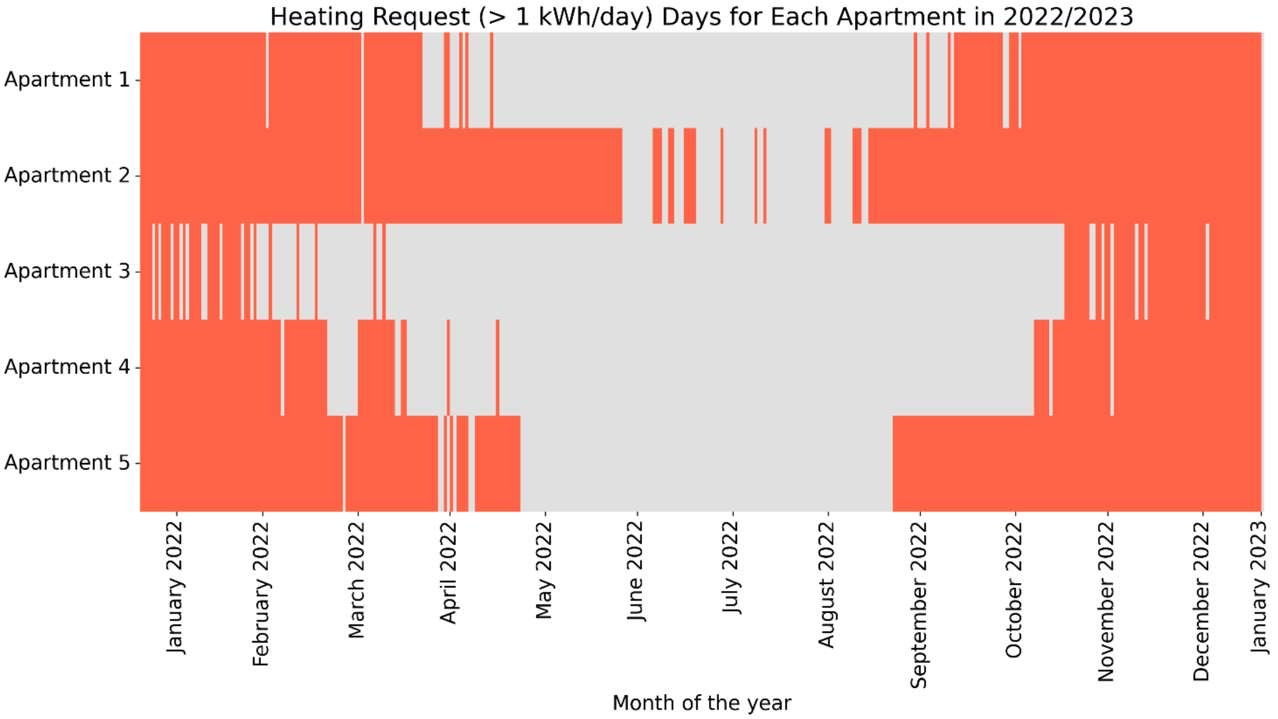


Figure 7: Days over the respective year where the heating use is higher than 1 kWh per day (red areas) and gray areas when the sum of heating is lower than 1 kWh per day for each household. The months are displayed with a tick mark at the end of the respective month.

3.1.3 Heating use with respect to outdoor temperature

Figure 8 displays the yearly heating use curves for each household, which represent the total daily heating use plotted as a function of the daily mean outdoor temperature based on the heating setpoint temperature (average across each room) shown in the legend. The figures are arranged according to their physical locations within the building (See Figure 3). For comparison, each heating signature curve has been fitted with a linear regression model and calculation of Root Mean Squared Error (RMSE) and Coefficient of Determination (R^2) [48] , highlighting the variations in heating behavior among the occupants/households.

Significant differences are observable in the heating use and the heating setpoint temperatures across the households. These differences reflect varying occupant preferences and behaviors and imply potential thermal interactions between households, such as heat transfer from one unit to another. The setpoint variations significantly influence each household's heating needs, with lower setpoints naturally resulting in reduced heating use and vice versa. Furthermore, the fitting of the linear regression illustrates the relationship of each household's heating system relative to outdoor air temperature. Households with steeper slopes (lower slope coefficients) on their signature curves suggest higher sensitivity to outdoor temperature changes, which could indicate variations in air exchange rates across the building (e.g., window opening and wind across the façade). The RMSE varies from 0.04 to 0.07, which indicates that the linear model is a fair predictor. Whereas the R^2 varies from 0.33 to 0.67, indicating that 33 % to 67 % has a strong relationship with 64% of the variance explained.

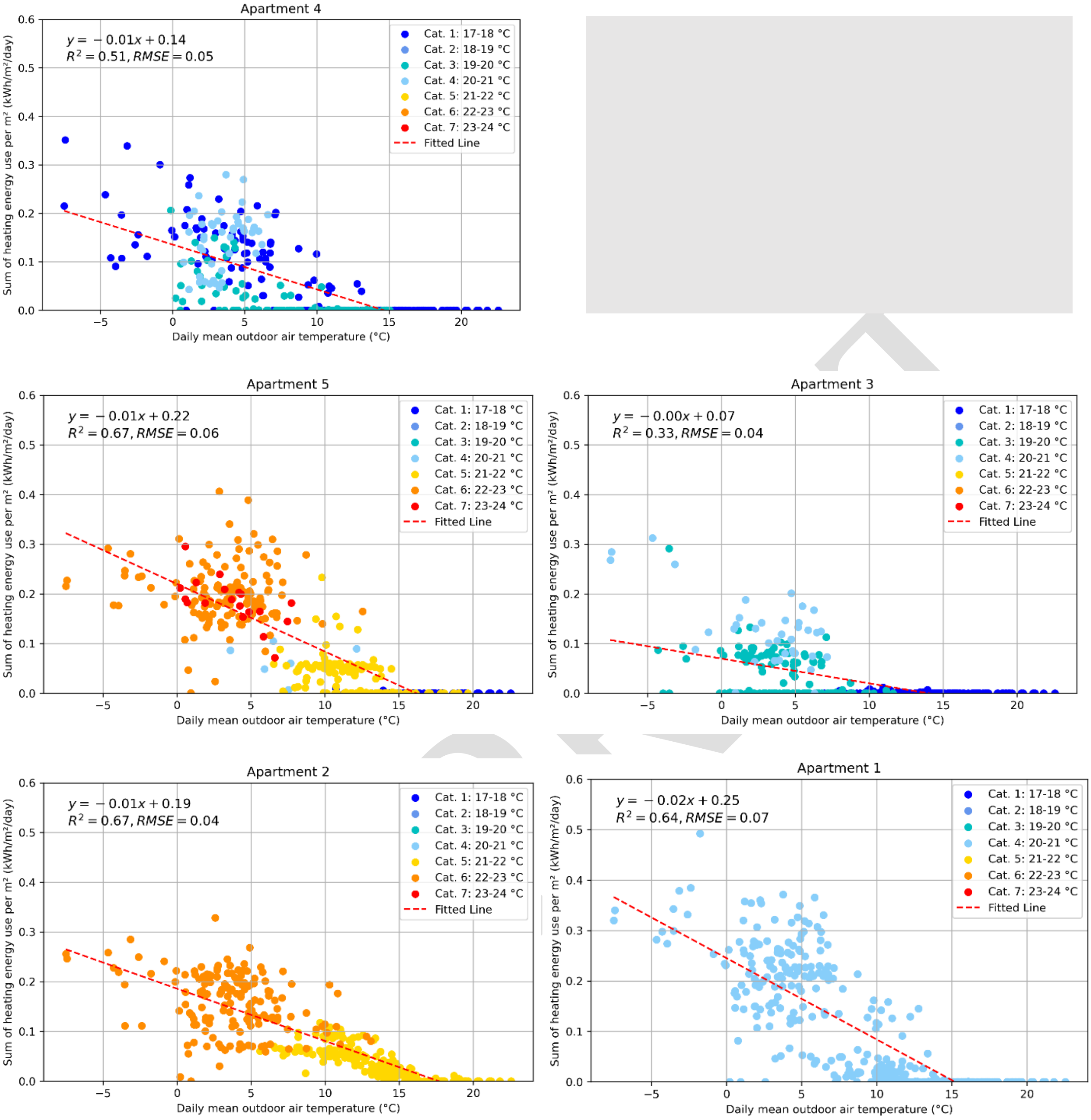


Figure 8: Yearly household heating signature curve based on heating setpoint temperature (19.01.22 – 19.01.23) with respect to the daily mean outdoor temperature.

Households 2 and 5 have similar setpoints at the higher end of the scale, while households 1, 3, and 4 have similar setpoints. This can suggest that households 2 and 5 prefer warmer indoor temperatures compared to the others. Due to these assumed comfort requirements, result in higher heating needs, as indicated by the larger intercept coefficient in the linear regression. Although household 1 has a lower setpoint (20 – 21°C) than households 2 (17 – 22.5 °C) and Households 5 (17 – 25 °C), but its energy signature, as determined by the fitted model, displays similar results to the latter. Similar to household 1, household 4 has the lowest setpoint. Yet, the heating system still operates when outdoor temperatures are at the lower end. Conversely, household 3, while displaying similar setpoints to household 4, does not require as much heating. This suggests that household 4 reaches colder indoor temperatures than household 3. Possibly due to the location (top household with additional heat losses through the roof). It might also have more infiltration if air gaps exist between the facade and roof.

3.2. Analyses of occupant practices using qualitative data

This section briefly describes the practices and everyday life of the five households. This is based on qualitative data from semi-structured interviews and includes descriptions of activities like window-opening, heating regulation, daily rhythms and routines, feedback and interaction with the building manager and/or janitor, and relations with neighbors. In addition, field notes were used to give descriptions of the households, the occupants, and the interview setting.

3.2.1 Household 1 – Oluf: Quiet life with energy use interest

In household 1 lives Oluf, a 65-year-old retired schoolteacher, who has lived in this household since the building was renovated in 2013. Despite having health issues, he appears perky with a sense of humor. He describes his life as quiet, primarily due to health issues, and he spends most of his time at home, watching television. However, Oluf engages in volunteer work at the harbor for a few hours each week to contribute to society as much as he can.

Despite his solitary lifestyle, maintaining good relationships with neighbors indicates a community-oriented aspect of his personality. Oluf describes his relationship with neighbors as good. Oluf follows a regular daily routine, indicating a desire for predictability and comfort in his daily life, waking up early and going to bed between 23:00 and 01:00. The household is sparsely decorated with a few pieces of furniture, with a few floor lamps and ceiling lights in the bedroom and bathroom. Because Oluf is frequently smoking inside, the household has a strong smell of cigarettes and brownish stains on the walls. To counteract this, he regularly opens windows, especially in the bedroom, to let in fresh air.

Oluf mentions that the ventilation is noisy, but that he has adapted to it. However, he leaves the internal doors open for better air circulation, though he slightly closes his bedroom door at night due to the noisy ventilation. He also mentioned that he always has the internal blinds down and says it is because of the possibility of looking from the households on the other side and solar glare at the television, but only during the winter.

He mentioned that he rarely adjusts the heating setpoint temperatures, only if it is particularly cold outside. He refers to the building manager (Matthew and/or Ryan), who mentioned that the occupants should modulate the heating setpoint temperature with a larger time between modulations to maintain comfort and achieve the desired temperature. He respects this but also mentions that he is generally satisfied with the indoor temperature, and he prefers to maintain comfort in simple ways, like wearing extra clothes instead of increasing the heating setpoint temperatures.

Oluf knows how the energy systems work and acknowledges that he is fortunate to live in such an energy-efficient building, especially now (energy-crisis in Europe 2023). He also has a keen interest in energy use, closely monitoring it through the energy use display. He is mainly focused on the ‘heating smiley’ and writes down all the energy use parameters and outdoor temperature every day in the evening in a dedicated diary, which he has meticulously done every day for the last 10 years. He compares these readings with previous years to manage his energy bills better. Figure 9 shows an example of a comparison of heating registration made by Oluf. Despite his interest in the ‘heating smiley’, he mentioned that he does not feel the need or interest for more feedback but might appreciate it in a paper format once a month. For example, the average indoor temperature is currently not visible in the feedback display.

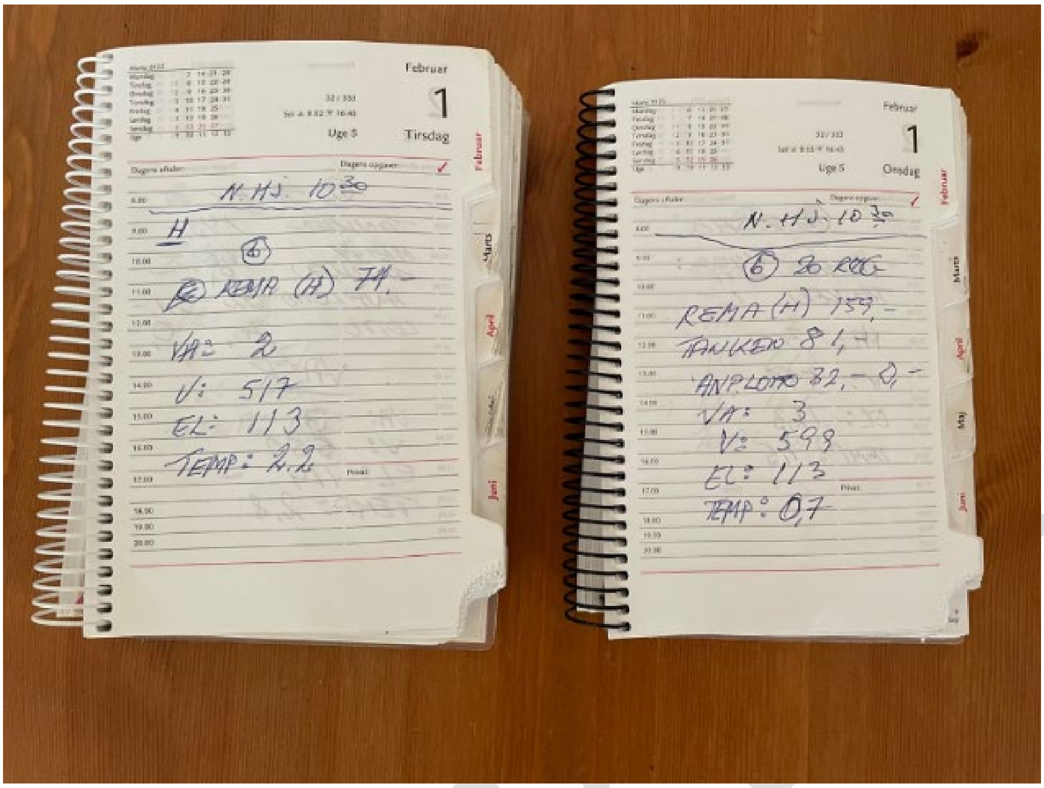


Figure 9: Occupant 1 (Oluf) register daily the energy use in a calendar/diary together with the daily shopping bill. The year 2022 is to the left, and 2023 is to the right.

3.2.2 Household 2 – Elsa: Clean, tidy and warm

In household 2 lives Elsa, a 75-year-old retired after-school teacher, who moved in right after the building renovation, at the same time as Oluf (household 1) and Hans (household 3). Her neat appearance and the thoughtful way she spoke about others made her seem welcoming and sincere. She is fond of knitting and writing cards and, therefore, enjoys the light in the kitchen during the day (no direct sunlight), where she spends quite some time. However, she usually sits on the sofa in the living room during the evening.

She mentioned that she is happy to have friendly and helpful neighbors. Around once a week, she has Olaf (household 1) over for a beverage, and he brings her flowers occasionally. They also occasionally discuss everyday life and the news around the world. Elsa classifies herself as a B-person who sleeps around 23:00. She makes sure to go out every other day to bike, exercise, play cards with friends, or help them with various tasks. She expresses that she prefers to stay active and healthy. The household is tidy, very clean, and has designated seating spaces, for example, when watching television or working on projects such as knitting.

Elsa is persistent with opening windows every day, and she does so during winter for at least 15 minutes after she wakes up unless it is very windy or cold. She says she used to be a smoker inside, and this window-opening habit is something she used to have. Now, she opens windows for fresh air but mentions that she does not like the ventilation as she feels it makes the household continuously colder. However, she understands it is for supplying fresh air. She also mentioned that she likes to have the sun entering her household, so she's persistent with always opening the blinds during the day but closing them at night. She likes to open all the internal doors but closes the bedroom door at night.

Elsa mentions that she does not compromise on heating, as she does not like to be cold. She says that she finds the heating prices cheap, which is very much linked to her satisfaction with this household. She says that she listens to the building managers (Matthew and/or Ryan) and should not frequently regulate the heating setpoint temperature but instead do it seasonally or weekly. However, she also mentioned that she's always cold in the evening and needs to almost always put on a sweater. She says she had radiators in her previous house and in her household. Sometimes, she misses a fireplace or the possibility of making a warmer zone.

She mentioned that she was inspired by Oluf (household 1) to start writing down her energy use every evening and has also done so for the last 10 years (see Figure 10). She is aware of how the energy system works and feels very fortunate regarding the current situation in the world. The most important smiley for her is the "heating smiley" even though she does not compromise on that, she still likes to keep an overview of it for her use. She also says she enjoys the energy display and has found several faults in the household. One time, the heating smiley was angry, and she had not been home, so she called the janitor. It turned out that a valve was leaking/broken in the technical room in her household. She is interested in more feedback and thinks it would be interesting to see how the different households use energy compared to her.

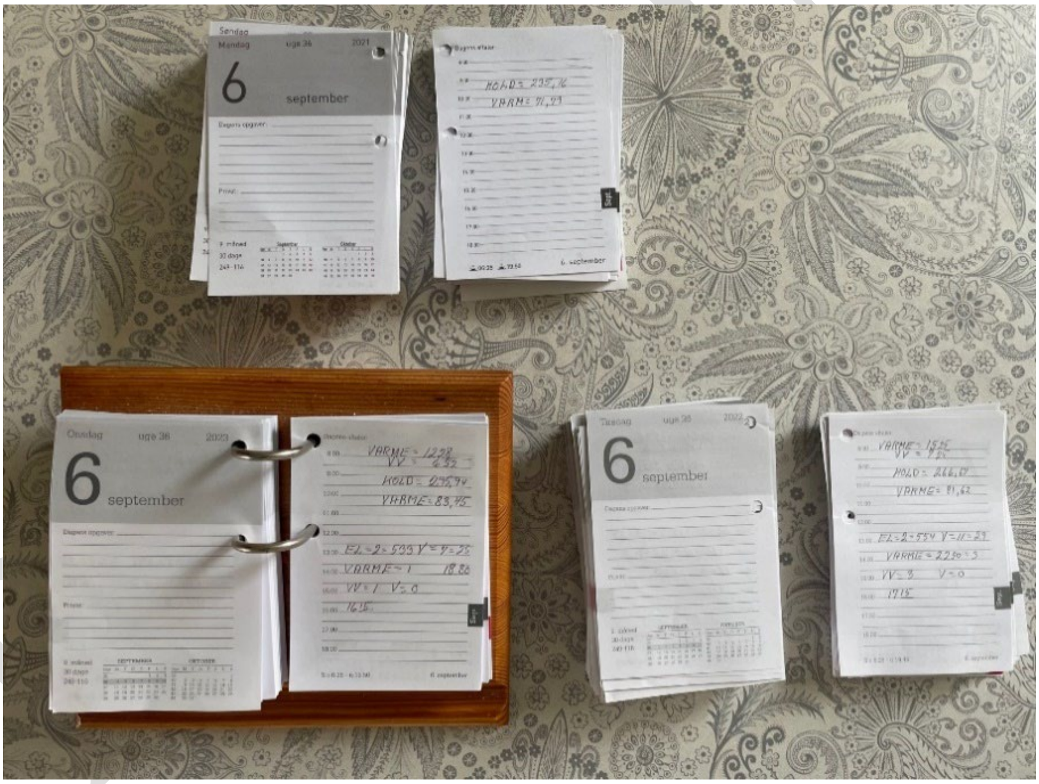


Figure 10: Occupant 2 energy use comparison diary. The year 2021 on the top, 2022 to the left and 2022 to the right.

3.2.3 Household 3 – Hans: Stability and familiarity

Hans lives in household 3. He is a 75-year-old retired welder who has lived in the household for 10 years (same as Oluf and Elsa). He says he's quite a routine person, and he usually wakes up around 06:00 to 08:00 and goes to sleep around 23:00/00:00. There is quite a lot of electrical equipment, such as repair equipment, drills and hammers. Hans lives a calm and quiet lifestyle, watching television (he especially likes to watch sports) and socializing with old colleagues once or twice weekly. He has a regular schedule and a daughter who visits weekly. The household is furnished with a medium to high density of furniture. The living room/kitchen has a large sofa, coffee table, and a television.

He says he is troubled with a bad back from his welder times. Thus, there is also a large, comfortable, and supporting chair in the middle of the living room, which he usually sits in. He has a laptop and a tablet but rarely uses it. The bad back hinders him from being as active as he wants.

As the household is located on the first floor, it has a bit more daylight, and he mentions that the curtains are usually open during the day and rarely closed. He mentions that he does not reflect on the ventilation. He acknowledges and appreciates that it is there and understands the concept of fresh air. He says he never opens windows or doors to the outside during the winter. On the contrary, he has all the internal doors open during the day, including the bathroom.

Hans expresses that he's always happy with the temperature. He typically wears pants and a sweater, and rarely regulates or changes during the winter. He has an old thermometer from his former job that he sometimes looks at during the summer but not necessarily during the winter. He says he does not modulate the setpoints. From the data the authors have insight into, it can be seen that they are adjusted, and it is suspected that the daughter does it.

Hans mentions that he uses the energy display at least once daily, and his most important smiley is the water. He said he had found several faults with this; once, the water smiley was angry, and it turned out to be a running toilet. However, he mentions that he's not necessarily interested in more feedback as this is the most technical feedback he has used. Hans' awareness of energy use appears to be relatively basic.

3.2.4 Household 5 – Kristoffer and Anna: Common ground

Kristoffer and Anna live in household 4, are both in their early 30s, and have lived in the household for nearly six years together. Their occupations include shipping manager and nursing. Kristoffer plays football two times a week and typically enjoys playing video games in the evenings. Anna enjoys various activities, but since her work schedule varies, she adapts to them. On the weekends, their activities typically involve relaxation, going out, staying at home, or having friends over.

Their home is modernly furnished, with light colors and modern paintings and decorations. They adjust their solar shading based on sunlight, especially to prevent glare on the television. However, they like the sun in the winter as it is rare and does not specifically heat during winter. They mentioned they use more candles during winter and especially during Christmas. Both to make it cozier, but also for local increase of temperature.

They mentioned that they don't pay much attention to the ventilation, except for its occasional noise. They keep their internal doors open except when the bedroom door is partially closed at night. They never open windows during winter, but occasionally open them during winter just for airing out or while cleaning. However, they sleep with the window slightly open due to differing preferences. Moreover, there is a frequent opening of the window in the office where he plays video games and occasionally smokes cigarettes.

Regarding temperature preferences, they're both on the same page regarding wanting colder temperatures in the bedroom and warmer temperatures in the bathroom and living room/kitchen. However, there are certain disagreements on temperature settings between them. He reports that he is very cold in the morning and does not prefer to have the window open during the night, which she does. She, on the contrary, is colder in the evenings. This has led to increased temperature modulation on the thermostat in the different rooms. In general, they mentioned that they adjust the setpoint seasonally based on the external weather conditions. Typically, during spring and autumn, they start opening/closing the windows more. This has led to individual coping strategies for temperature regulation. She typically uses a blanket, and he typically puts on a sweater if feeling discomfort.

Similar to Elsa, they have the most experience with a radiator as a heating source and liked that they could create a “warm zone” and a “cold zone” within a short period. They cannot do this similarly with the underfloor heating but are very satisfied with the low heating costs. They mentioned that this is an absolute factor for continuing to live there. They also briefly mentioned that they understand that energy is produced cleaner than with, for example, district heating.

They are primarily interested in the ‘electricity smiley’ and pay particular attention to when there are sunglasses on. For example, this makes them feel better when washing clothes or putting on the dishwasher. They mentioned that the heating costs are relatively low, leading to a focus on comfort rather than energy savings. They are positive about receiving more feedback on changing behaviors. However, with some hesitation, as they expressed, they don't know what that indicates. Anna is very interested, but Kristoffer is more hesitant as he rarely uses the display.

3.2.5 Household 4 – Gerda: Sunlit and cat

In household 5 lives Gerda, a 30-year-old librarian. She has lived here since 2021, together with her 4-year-old active indoor cat. Due to the indoor cat, she has all the internal doors open so the cat can freely move and have some more space. She says she is also typically a routine person. She gets up between 06:00/07:00 and goes to bed around 21:00/22:00, depending on if it is a weekday or weekend. Her typical schedule after work involves making food, relaxing and watching television, doing some minor workouts, or using the indoor bike that she has in the household. She lived in another place just a couple of blocks from where she lives now, a much smaller place driven by the cost of rent and utilities. She is very aware of how fortunate they are in her current household regarding the cost of living and energy prices for electricity, heating, and water. She is generally pleased with the household, especially the direct light on the South façade. She keeps all her blinds open during the winter.

She mentioned that she likes to be social; she has friends coming over approximately once a week, and she goes to see her sister and parents around once a week. She says she typically airs out during weekends and washes clothes and linens. Also, she typically does not open windows due to her cat. She sometimes opened the windows and put a rock she had collected from the outside as a barrier.

She uses the energy feedback display daily, paying extra attention to the electricity smiley to wash clothes. She said she gladly uses electricity when the smiley has sunglasses on. She also mentioned that she does not regulate setpoint very frequently and prefers putting on a sweater or wool socks if it is colder than preferred. She knows passive strategies and mentions that she often leaves the oven open after cooking a long meal. She only regulates the setpoint seasonally when it becomes cold or warm outside. She modulates more frequently in the bathroom because she prefers it to be a bit warmer there. She has experienced faults in the heating system, such as warm areas on the floor; thus, she had to reset the sensors.

She said she is interested in seeing more indoor climate data, especially on room level. She is not interested in the feedback on an app, she prefers the existing monitor. She would be interested in comparing both energy and indoor climate data for similar households in the building. She said she could agree on feedback once a week but preferably once a month every other week.

4. Discussions on key findings

This sequential explanatory mixed-method study combined two approaches (quantitative data analysis of heating use, setpoint temperature and room temperature, and semi-structured qualitative interviews) to investigate the role of six occupants, five households in a residential building of their heating behavior and practices. Six cross-cutting themes are further discussed below.

The first theme was to learn to live with a new technical system. When the occupants moved into the building, the building managers (Matthew and Ryan), provided them with essential guidance on the operation of the building's systems, focusing particularly on the management of the heating system. This advice was not intended to restrict changes to the setpoints but to educate the occupants on the nature of the building's heating system, which is slow to react to adjustments (high time constant). This knowledge was provided to help the occupants optimize their comfort while understanding the limitations and capabilities of the system. This topic was recurrent in the interviews with the occupants and can be interpreted as a trust and respect for recommendations in the community. Furthermore, across the households, the function of the building managers (Matthew and Ryan) was appreciated. Each household had a feedback display installed, which was generally well received by the occupants, who said they used it daily and were affected by the 'smileys' in a good way. Interestingly, each household had one specific parameter they were most interested in. Where the older households preferred the heating feedback (smiley), the younger households preferred the electricity feedback (smiley). Two of the older occupants (older than 65 years) also had a routine of writing down the energy use for heating, electricity, water, and the outdoor air temperature in a book daily. However, a larger sample is needed to establish whether there could be an age effect in these differences in practices and preferences.

The second theme dealt with the balance between clothing and indoor temperature. One of the noticeable behavioral adaptations observed across multiple households (Elsa/2, Hans/3, Kristoffer and Anna/5, Gerda/4) is the choice to change their clothing behavior when in discomfort instead of adjusting the heating setpoint. This choice can stem from an understanding that any setpoint adjustment will be gradual due to the heating system's long-time constant. This practice reflects a recurrent theme in residential energy use: adaptive comfort behaviors as an alternative to mechanical heating, which aligns with the findings of the other studies [51]. This behavior can be considered significant because it illustrates a form of energy literacy where occupants understand and respond to the energy implications of their comfort choices. It highlights an essential aspect of residential energy use: comfort management is not solely reliant on building technology but is also significantly influenced by occupant behavior and everyday practices, which is also agreed upon in existing literature [22,35]. Also, as the room temperatures and setpoints were found to be varying, but occupants generally articulated that they were comfortable with their living conditions. Some did report discomfort, for example, a common element that arose from the interviews was the inability to use a radiator to create a thermal zone, but they adapted with clothes or other actions, as it is also well-known from previous studies [49,50].

The third theme was about what could be called a 'struggle' over heating practices. Only household 4 consisted of more than one occupant. The disagreement in temperature preferences between Kristoffer and Anna could potentially be causing increased energy usage. For instance, the practice of frequent adjustment of heating setpoints and discussions on window openings reflect not just individual choices but a response to the social structures and configurations in their household. Some previous studies also touch upon the importance of social relations and the 'negotiation' of heating practices [28,52]. In the quantitative data, this household had the highest heating use of all the occupants, which suggests that consumption might reflect such 'negotiations' or 'struggles'.

The fourth theme was about the discrepancy between energy awareness and energy practice. Oluf/1 represents what could be called an active energy consumer; he neatly follows his energy use by writing it into a book. However, due to this consistent monitoring of energy use and active engagement in energy-saving practices, such as adjusting clothing levels rather than changing the heating setpoint temperature, it is hypothesized that the occupant's overall energy use will be lower than individuals who are less energy-aware. However, because Oluf/1 opens and closes the windows frequently due to heavy smoking inside, even during winter, his heating use will be higher or comparable to that of an occupant with a higher heating setpoint temperature due to this action. This can be seen in the energy signature curves (Figure 5), where Elsa/2 and Oluf/1 have close to the same heating use, but Oluf has lower heating setpoints, indicating that the room temperature is more often below the setpoint, inducing heating (Table 2). However, Kristoffer's/4 window-opening behavior while smoking cigarettes and playing video games in the office during the evenings or weekends might not strongly affect the heating use. This might be due to higher heat load from gaming computers and screens or the location of the sensor/thermostat. In Table 3, the quantitative analysis revealed that the room temperature is 99 % of the time higher than the heating setpoint, thus not inducing heating use as the setpoint is lower than the measured room temperature. This can be confirmed in Figure 11 in Appendix A. These examples illustrate how engagement and awareness might contradict practices. However, the diary with registration on the energy use of Oluf/1 and Elsa/2 highlights the potential of occupant-led energy monitoring as a component of broader energy management strategies in residential buildings. Their proactive measures demonstrate how informed and engaged occupants can effectively complement energy overview feedback systems, potentially leading to more refined energy savings and enhanced comfort management.

Moreover, their actions suggest that providing occupants with simple, understandable feedback mechanisms, like the 'heating smiley', can significantly enhance engagement with energy management systems. This engagement fosters a sense of responsibility and control over their energy use, which can be particularly empowering for various types of households, for example for more committed approaches to new technologies [53,54].

In contrast to the active energy consumers described above, the fifth and final theme zooms in on an example of an inactive or passive energy consumer. At 75 years old and living with the aftereffects of a physically demanding job, Hans/3 values stability and simplicity in his daily life. His approach to the feedback display in his household reflects a broader area observed among certain demographics, particularly older individuals or those accustomed to more traditional technologies, for example, routine and comfort, physical limitations (bad back), and technical engagement. However, Hans interacts with the feedback display, and his engagement is basic and focused on immediate needs (e.g., the water smiley related to a running toilet). Thus, Hans/3 exemplifies a passive energy consumer, which could be referred to as practicing a more reluctant approach to smart home technologies [54], for example, due to a combination of personal habits, physical limitations, and comfort with existing routines, which illustrates the importance of previous experiences form current heating practices [30].

5. Conclusion and suggestions for future studies

Current approaches to investigating energy-related occupant behavior and practices in residential buildings tend to focus on the technical- or the social aspects of heating behavior and practices. This study used a sequential explanatory mixed-methods approach that combined objective and subjective analyses. The current study focuses on a multi-story residential building to investigate the influences of energy-related decisions and shared heating practices among occupants, less commonly studied in the existing literature. The article seeks to contribute to developing more effective strategies for promoting energy efficiency in residential contexts, especially in low-energy buildings, guided by the following research question: *What are the main factors affecting energy-related occupant behavior, specifically heating practices, in a low-energy multi-story residential building, and how do these factors contribute to energy efficiency?*

The quantitative analysis showed substantial differences in heating practices (human-building interactions) across the households. The occupants were found to have both 1) very varying setpoints in the different rooms in their households (20 °C and 25 °C at the same time and room), 2) frequency of modulating setpoints (from two yearly modulations across three rooms to 21 yearly modulations across four rooms) and 3) varying heating season (from 90 to 301 days). Room temperature varied due to the horizontal location of each apartment in relation to solar gain, window opening (not monitored quantitatively, but addressed in the qualitative part), heat losses, internal gains such as electrical equipment and occupancy. Thus, the heating use varies across households. In the analysis of heating use in relation to the outdoor temperature, some households have similar trends on colder days, even though they have lower setpoints (household 4 vs household 2). This could be the frequent window opening, differences in occupancy, electricity use (internal gains), and leakages that provide differences in heat loads and losses. However, the qualitative descriptions indicate shared practices regarding monitoring energy use (for example writing down the energy- and water use in a diary every evening). The latter suggests that despite individual differences, households living in the same building might still share and transmit heating practices, which might relate to interpersonal trust. The presence of shared practices, coupled with interpersonal trust, underscores the potential of community-focused strategies to enhance energy efficiency in residential settings. These insights can contribute to the inclusion of social dynamics in energy policy and building management. This can further be used to promote technological solutions and contribute to communal support for sustainable energy use. Future research should further explore these interactions over time and across diverse residential buildings to refine and expand upon our findings.

Different occupant routines and practices compromise heating use in different ways; to change this, interventions should include educational programs that enhance occupants understanding of energy efficiency and structured feedback mechanisms that make the consequences of their actions visible and comprehensible. Furthermore, understanding these diverse heating practices and behaviors offers crucial insights for developing more effective, occupant-centered energy management strategies. It underscores the potential of using automated or adaptive heating systems that can adjust based on real-time data on occupancy, room usage, outdoor temperatures, and solar gains. Future studies can investigate this potential by, for example, Occupant-Centric Key Performance Indicators (OC KPIs) to better understand/gain insight into direct energy-related occupant behavior more suitable for the building operator or integrated into an energy feedback display.

Data Statement

The curated dataset from the five households with heating use, heating setpoint temperature, room temperature, the code for figures and analyses, and supplementary material (interview guide) can be found at the following GitHub repository: https://github.com/aauphd2024/energy-related-occupant-behavior. The data is available upon request to the corresponding author.

Acknowledgments

A huge thank you to "Matthew and Ryan" for their assistance in coordinating the interviews and household visits. Also, the authors are very grateful to the occupants for their generosity in sharing their time for the interviews and their warm hospitality during the visits to their homes.

To the AAU Ph.D. Corner Office (Daniel Leiria, Simon Pommerencke Melgaard, Markus Shaffer & Martin Frandsen) at Aalborg University, Built Environment – thank you for your support and everyday discussions.

Funding

The authors gratefully acknowledge the support from the European Union's Horizon 2020 research and innovation programme and several partners through the research project "Self-Assessment Towards Optimization of Building Energy" (SATO, https://www.sato-project.eu/), grant agreement No. 957128.

References

[1] A. Heydarian, C. McIlvennie, L. Arpan, S. Yousefi, M. Syndicus, M. Schweiker, F. Jazizadeh, R. Rissetto, A.L. Pisello, C. Piselli, C. Berger, Z. Yan, A. Mahdavi, What drives our behaviors in buildings? A review on occupant interactions with building systems from the lens of behavioral theories, Building and Environment 179 (2020) 106928. https://doi.org/10.1016/j.buildenv.2020.106928.

[2] B.F. Balvedi, E. Ghisi, R. Lamberts, A review of occupant behaviour in residential buildings, Energy and Buildings 174 (2018) 495–505. https://doi.org/10.1016/j.enbuild.2018.06.049.

[3] T. Hong, S.C. Taylor-Lange, S. D'Oca, D. Yan, S.P. Corgnati, Advances in research and applications of energy-related occupant behavior in buildings, Energy and Buildings 116 (2016) 694–702. https://doi.org/10.1016/j.enbuild.2015.11.052.

[4] H.P. Tuniki, A. Jurelionis, P. Fokaides, A review on the approaches in analysing energy-related occupant behaviour research, Journal of Building Engineering 40 (2021) 102630.

[5] P. van den Brom, A.R. Hansen, K. Gram-Hanssen, A. Meijer, H. Visscher, Variances in residential heating consumption – Importance of building characteristics and occupants analysed by movers and stayers, Applied Energy 250 (2019) 713–728. https://doi.org/10.1016/j.apenergy.2019.05.078.

[6] Y.G. Yohanis, Domestic energy use and householders' energy behaviour, Energy Policy 41 (2012) 654–665. https://doi.org/10.1016/j.enpol.2011.11.028.

[7] A.R. Hansen, K. Gram-Hanssen, Over- and underconsumption of residential heating: Analyzing occupant impacts on performance gaps between calculated and actual heating demand, J. Phys.: Conf. Ser. 2654 (2023) 012062. https://doi.org/10.1088/1742-6596/2654/1/012062.

[8] A. Mahdavi, C. Berger, Predicting Buildings' Energy Use: Is the Occupant-Centric "Performance Gap" Research Program Ill-Advised?, Front. Energy Res. 7 (2019). https://doi.org/10.3389/fenrg.2019.00124.

[9] A. Mahdavi, C. Berger, H. Amin, E. Ampatzi, R.K. Andersen, E. Azar, V.M. Barthelmes, M. Favero, J. Hahn, D. Khovalyg, H.N. Knudsen, A. Luna-Navarro, A. Roetzel, F.C. Sangogboye, M. Schweiker, M. Taheri, D. Teli, M. Touchie, S. Verbruggen, The Role of Occupants in Buildings' Energy Performance Gap: Myth or Reality?, Sustainability 13 (2021) 3146. https://doi.org/10.3390/su13063146.

[10] R.C. Sonderegger, Movers and stayers: The resident's contribution to variation across houses in energy consumption for space heating, Energy and Buildings 1 (1978) 313–324. https://doi.org/10.1016/0378-7788(78)90011-7.

[11] L. Lutzenhiser, Social and Behavioral Aspects of Energy use, Annual Review of Energy and the Environment 18 (1993) 247–289. https://doi.org/10.1146/annurev.eg.18.110193.001335.

[12] L. Lutzenhiser, A cultural model of household energy consumption, Energy 17 (1992) 47–60. https://doi.org/10.1016/0360-5442(92)90032-U.

[13] E. Shove, G. Walker, What Is Energy For? Social Practice and Energy Demand, Theory Culture Society 31 (2014) 41–58. https://doi.org/10.1177/0263276414536746.

[14] K. Gram-Hanssen, Understanding change and continuity in residential energy consumption, Journal of Consumer Culture 11 (2011) 61–78. https://doi.org/10.1177/1469540510391725.

[15] Y. Li, Y. Yamaguchi, J. Torriti, Y. Shimoda, Modeling of occupant behavior considering spatial variation: Geostatistical analysis and application based on American time use survey data, Energy and Buildings 281 (2023) 112754. https://doi.org/10.1016/j.enbuild.2022.112754.

[16] S. Chen, W. Yang, H. Yoshino, M.D. Levine, K. Newhouse, A. Hinge, Definition of occupant behavior in residential buildings and its application to behavior analysis in case studies, Energy and Buildings 104 (2015) 1–13.

[17] A. Wagner, W. O'Brien, B. Dong, eds., Exploring Occupant Behavior in Buildings, Springer International Publishing, Cham, 2018. https://doi.org/10.1007/978-3-319-61464-9.

[18] L.K. Aagaard, The meaning of convenience in smart home imaginaries: tech industry insights, Buildings and Cities 2 (2021) 568–582.

[19] K. Gram-Hanssen, Teenage consumption of cleanliness: how to make it sustainable?, Sustainability: Science, Practice, & Policy 3 (2007).

[20] A.R. Hansen, L.V. Madsen, H.N. Knudsen, K. Gram-Hanssen, Gender, age, and educational differences in the importance of homely comfort in Denmark, Energy Research & Social Science 54 (2019) 157–165. https://doi.org/10.1016/j.erss.2019.04.004.

[21] T. Jack, Cleanliness and consumption: Exploring material and social structuring of domestic cleaning practices, International Journal of Consumer Studies (2016) 1–9. https://doi.org/10.1111/ijcs.12315.

[22] L.V. Madsen, K. Gram-Hanssen, Understanding comfort and senses in social practice theory: Insights from a Danish field study, Energy Research & Social Science 29 (2017) 86–94. https://doi.org/10.1016/j.erss.2017.05.013.

[23] Y. Strengers, Comfort expectations: the impact of demand-management strategies in Australia, Building Research & Information 36 (2008) 381–391. https://doi.org/10.1080/09613210802087648.

[24] E. Shove, Comfort, Cleanliness and Convenience: The Social Organization of Normality, Bloomsbury Academic, 2003.

[25] O. Coutard, E. Shove, Infrastructures, Practices and the Dynamics of Demand, in: Infrastructures in Practice - The Dynamics of Demand in Networked Societies, Routledge, New York, 2019.

[26] M. Sahakian, H. Rau, E. Grealis, L. Godin, G. Wallenborn, J. Backhaus, F. Friis, A.T. Genus, G. Goggins, E. Heaslip, E. Heiskanen, M. Iskandarova, C. Louise Jensen, S. Laakso, A.-K. Musch, C. Scholl, E. Vadovics, K. Vadovics, V. Vasseur, F. Fahy, Challenging social norms to recraft practices: A Living Lab approach to reducing household energy use in eight European countries, Energy Research & Social Science 72 (2021) 101881. https://doi.org/10.1016/j.erss.2020.101881.

[27] K. Matschoss, F. Fahy, H. Rau, J. Backhaus, G. Goggins, E. Grealis, E. Heiskanen, T. Kajoskoski, S. Laakso, E.-L. Apajalahti, Challenging practices: experiences from community and individual living lab approaches, Sustainability: Science, Practice and Policy 17 (2021) 136–152.

[28] T. Hargreaves, L. Middlemiss, The importance of social relations in shaping energy demand, Nature Energy 5 (2020) 195–201. https://doi.org/10.1038/s41560-020-0553-5.

[29] A.R. Hansen, M.H. Jacobsen, Like parent, like child: Intergenerational transmission of energy consumption practices in Denmark, Energy Research & Social Science 61 (2020) 101341. https://doi.org/10.1016/j.erss.2019.101341.

[30] A.R. Hansen, 'Sticky' energy practices: The impact of childhood and early adulthood experience on later energy consumption practices, Energy Research & Social Science 46 (2018) 125–139. https://doi.org/10.1016/j.erss.2018.06.013.

[31] J.W. Creswell, V.L.P. Clark, Designing and Conducting Mixed Methods Research, 2nd edition, SAGE Publications, California, USA, 2013.

[32] A. Palm, Peer effects in residential solar photovoltaics adoption—A mixed methods study of Swedish users, Energy Research & Social Science 26 (2017) 1–10. https://doi.org/10.1016/j.erss.2017.01.008.

[33] F.C. Guasselli, A. Vavouris, L. Stankovic, V. Stankovic, S. Didierjean, K. Gram-Hanssen, Smart energy technologies for the collective: Time-shifting, demand reduction and household practices in a Positive Energy Neighbourhood in Norway, Energy Research & Social Science 110 (2024) 1–12. https://doi.org/10.1016/j.erss.2024.103436.

[34] B.K. Sovacool, J. Axsen, S. Sorrell, Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design, Energy Research & Social Science 45 (2018) 12–42. https://doi.org/10.1016/j.erss.2018.07.007.

[35] A. Marszal-Pomianowska, S.P.A.K. Larsen, K. Gram-Hanssen, P. Heiselberg, Thermal conditions in households and assessment of building's flexibility potential. Variations in time, space and between dwellings, Building and Environment 206 (2021) 108353. https://doi.org/10.1016/j.buildenv.2021.108353.

[36] T. Hong, D. Yan, S. D'Oca, C. Chen, Ten questions concerning occupant behavior in buildings: The big picture, Building and Environment 114 (2017) 518–530. https://doi.org/10.1016/j.buildenv.2016.12.006.

[37] Social-, Bolig- og Ældreministeriet, Bekendtgørelse om bygningsreglement 2018 (BR18), 2019. https://www.retsinformation.dk/eli/lta/2019/1399 (accessed January 26, 2024).

[38] S. Aggerholm, Bygningers energibehov: Beregningsvejledning, 6th ed., Statens Byggeforskningsinstitut, Aalborg Universitet, 2018.

[39] K.H. Andersen, A. Marszal-Pomianowska, B. Jokubauskis, P.K. Heiselberg, Influence of Temporal- and Spatial Resolutions on Building Performance Simulation Models: A Danish Residential Building Case Study, J. Phys.: Conf. Ser. 2600 (2023) 132007. https://doi.org/10.1088/1742-6596/2600/13/132007.

[40] K.H. Andersen, H. Johra, M. Schaffer, A. Marszal-Pomianowska, H.N. Knudsen, P.K. Heiselberg, W. O'Brien, Exploring occupant detection model generalizability for residential buildings using supervised learning with IEQ sensors, Building and Environment (2024) 111319.

[41] K. O'Sullivan, P. Howden-Chapman, Mixing methods, maximising results: Use of mixed methods research to investigate policy solutions for fuel poverty and energy vulnerability, Indoor and Built Environment (2017) 1420326X17707327. https://doi.org/10.1177/1420326X17707327.

[42] K.H. Andersen, A. Marszal-Pomianowska, H.N. Knudsen, H. Johra, S.P. Melgaard, M.Z. Dahl, P.A. Hundevad, P.K. Heiselberg, Room-based Indoor Environment Measurements and Occupancy Ground Truth Datasets from Five Residential Apartments in a Nordic Climate, Department of the Built Environment, Aalborg University, 2023. https://doi.org/10.54337/aau550646548.

[43] https://opendatadocs.dmi.govcloud.dk/DMIOpenData, (n.d.).

[44] https://www.sato-project.eu/, in: n.d.

[45] https://github.com/aauphd2024/energy-related-occupant-behavior, (n.d.).

[46] M. Berge, J. Thomsen, H.M. Mathisen, The need for temperature zoning in high-performance residential buildings, J Hous and the Built Environ 32 (2017) 211–230. https://doi.org/10.1007/s10901-016-9509-2.

[47] Y. Liu, C. Song, Y. Wang, D. Wang, J. Liu, Experimental study and evaluation of the thermal environment for sleeping, Building and Environment 82 (2014) 546–555. https://doi.org/10.1016/j.buildenv.2014.09.024.

[48] https://www.geeksforgeeks.org/python-coefficient-of-determination-r2-score/, (n.d.).

[49] A.R. Hansen, K. Gram-Hanssen, H.N. Knudsen, How building design and technologies influence heat-related habits, Building Research & Information 46 (2018) 83–98. https://doi.org/10.1080/09613218.2017.1335477.

[50] A. Meinke, M. Hawighorst, A. Wagner, J. Trojan, M. Schweiker, Comfort-related feedforward information: occupants' choice of cooling strategy and perceived comfort, Building Research & Information 45 (2017) 222–238. https://doi.org/10.1080/09613218.2017.1233774.

[51] S.P.A.K. Larsen, K. Gram-Hanssen, A. Marszal-Pomianowska, Smart home technology enabling flexible heating demand: implications of everyday life and social practices, ECEEE 2019 Summer Study Proceedings (2019) 865–873.

[52] C. Butler, K.A. Parkhill, N.F. Pidgeon, Energy consumption and everyday life: Choice, values and agency through a practice theoretical lens, Journal of Consumer Culture 16 (2016) 887–907. https://doi.org/10.1177/1469540514553691.

[53] S.P.A.K. Larsen, K. Gram-Hanssen, When Space Heating Becomes Digitalized: Investigating Competencies for Controlling Smart Home Technology in the Energy-Efficient Home, Sustainability 12 (2020) 6031. https://doi.org/10.3390/su12156031.

[54] L.V. Madsen, A.R. Hansen, S.P.A.K. Larsen, Embodied competencies and smart home technology in energy use: three ways users integrate smart heating systems in everyday practices, Energy Efficiency 16 (2023) 55. https://doi.org/10.1007/s12053-023-10138-0.

Appendix A: Indoor room temperature time series per household

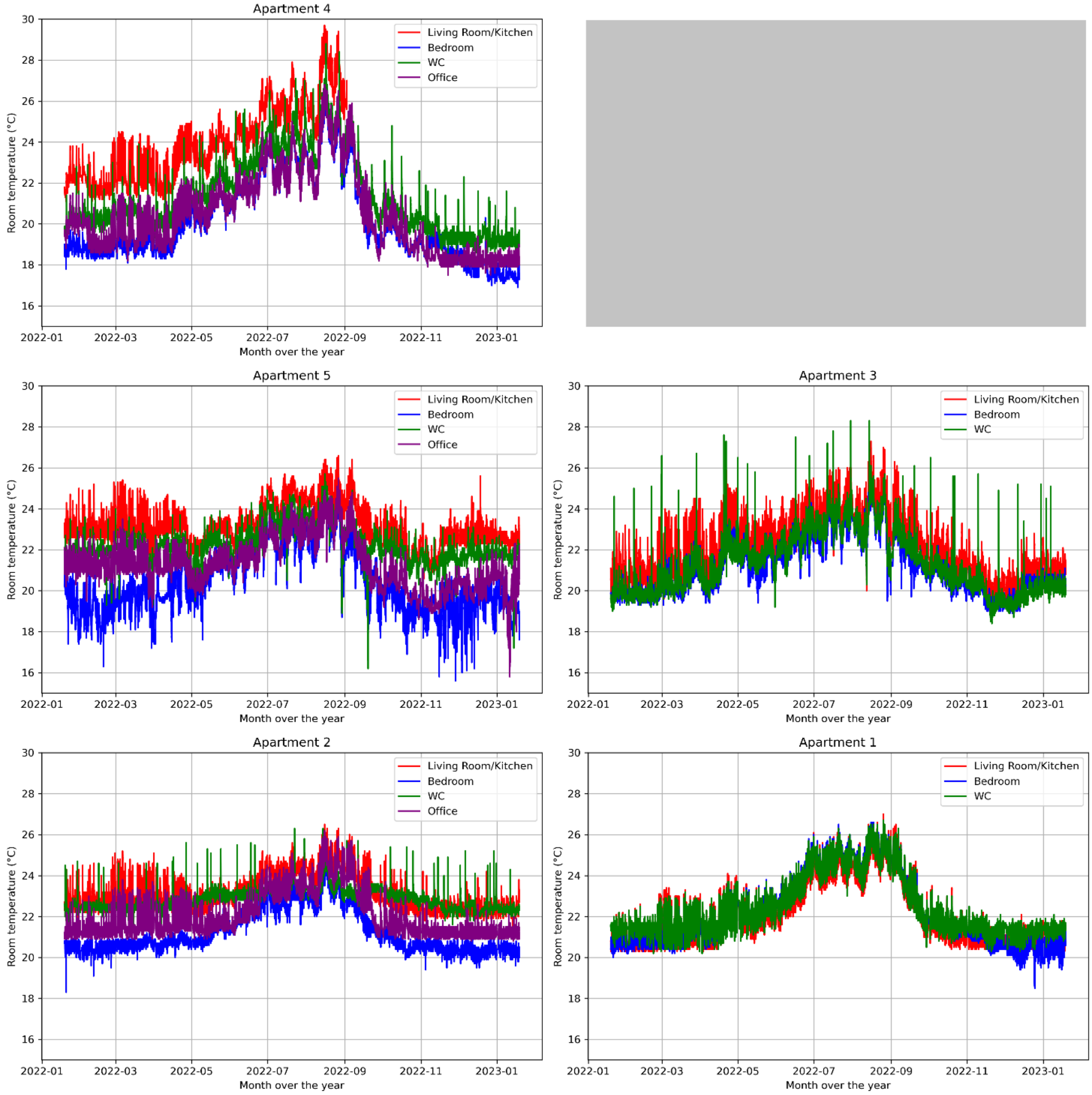


Figure 11: Indoor room temperature time series per household.