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Original research article

Is it a match? Smart home energy management technologies and user comfort practices in German multi-apartment buildings

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ABSTRACT

Energy-savings from smart home technologies (SHT) are a topic of considerable debate: While proponents of SHT emphasise the potential to reduce heating energy consumption and facilitate energy flexibility, critics highlight real-world challenges and a lack of evidence of actual savings. This study provides insights into SHT's actual saving potential and reveals essential mechanisms of occupant-technology interaction.

Based on social practice theory, this paper explores how occupants integrate SHT into their everyday comfort practices. Furthermore, it assesses the resulting impacts on heating energy consumption and compares these interactions to those within conventional building settings. The interactions with a pilot SHT are evaluated in 137 apartments in two newly constructed multi-apartment buildings. For comparison, a survey of households in conventional buildings, which vary in age, size and heating demand, is analysed. The case study employs a mixed-methods approach, based on standardised surveys, house tours, and measurement data, including metered energy consumption and indoor temperatures.

The findings suggest that households in conventional German buildings have become accustomed to temperature variations within apartments. However, a preference for thermal variation appears to conflict with the dominant features of SHT, which, as this study implies, tend to produce more homogeneous indoor temperatures. The study identifies four distinct interaction patterns based on an in-depth analysis of heating comfort practices. These patterns vary in how well material settings align with comfort practices, ranging from low to high efficiency. The results indicate that SHT does not offer a 'matching' one-size-fits-all solution for residents' diverse needs and heating demands.

1. Introduction

For the sustainable transformation of the residential building stock, it is essential to reduce its energy consumption for space heating. In the EU, this accounts for 18 % of total final energy consumption [1,2]. Innovative approaches such as smart home energy management technologies (SHT) [3], more commonly referred to simply as smart home technologies [4,5], are attracting growing interest because of their "great potential to provide cost-effective and significant energy savings" [6]. However, as for many other efficiency technologies, current research on such SHT points to a performance gap between the claimed savings potential, often estimated at up to 30 % [7,8], and actual savings achieved in real-world implementations [9,10].

Such performance issues have often been regarded separately: Technological issues on the one hand and behavioural problems on the other, a phenomenon Grandclément et al. [11] called the 'building versus behaviour approach'. In contrast, more recent research increasingly focuses on the interactions between occupants and technologies. In the domain of SHT, for example, researchers look at how introducing such technologies changes everyday space heating and comfort practices and the implications this has for heating energy consumption [12–14]. Even though much of this research is concerned with the impacts on temperature [15] and energy patterns [12], there remains a need to analyse the interaction between SHT and different comfort practices as well as its impacts on their energy performance for space heating in a larger sample of dwellings.

In this study, I build on the abovementioned insights when presenting findings from a case study with 137 apartments in two multi-apartment blocks. In this living lab, a SHT – still in development – has been implemented for the first time on a grander scale. The technology combines two features typical of SHT to optimise space heating energy consumption: First, occupant-centred control, and second, demand-

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based regulation [3]. The study aims to investigate how such a technology's behaviour aligns with other building properties and a variety of typical comfort practices. And it analyses the effects of the resulting interaction patterns on the energy performance of individual dwellings. The distinctive focus on technology in the early stages of development allows for examining the underlying assumptions and the challenges to increase the energy performance as intended by their designers. The study contributes to understanding systematic discrepancies between the assumptions inscribed into such technologies and everyday comfort practices. As will be shown, these discrepancies lead to a lack of space heating energy savings in real-world settings.

In studying households' habitual and routinised doings, social practice theory provides a framework well suited for considering material aspects of building technologies [16,17]. I use a mixed-methods socio-technical research design to examine three dimensions of these interactions: First, the material affordances of SHT and their consequences for potential use by occupants. Second, the typical patterns of comfort practices as they have evolved in German residential buildings – the majority of which are at best moderately insulated [18] and three-quarters of which are still heated with conventional oil- or gas-based heating systems [19]. And third, the effects of SHT on heating energy savings and how they depend on whether comfort practices remain stable or change in newly constructed buildings equipped with SHT.

The study's principal findings demonstrate, in accordance with previous research on such systems, that SHT is based on the assumption that connected living areas are evenly heated both spatially and over time. In this case, patterns of uniform indoor temperatures are reinforced, especially in well-insulated buildings. The study can also provide further evidence that many households' practices lead to varying indoor thermal conditions – even in material settings designed for uniformity. In the worst case, this not only impairs the energy performance of individual dwellings but, via feedback loops, also the overall efficiency of the smart buildings.

By comparing the interactions of material settings and comfort practices between older, less energy-efficient buildings and newer, more efficient buildings, the study also helps to explain shifts from prebound effects in the former [20] to energy performance gaps (EGP) [21,22] in the latter.[1]

2. Background and objectives

2.1. Social practice theory as an analytical perspective

The analysis in this paper is inspired and informed by a practice-theoretical view. Such a framework is particularly suited for combining social with physical and technical data [23,24]. Combining these data is necessary to analyse how temperature patterns and energy consumption for space heating result from everyday comfort practices and the material arrangements with which they are aligned.

Following Galvin and Sunikka-Blank [16], I use social practice theory as a heuristic device to understand the co-evolution between occupants' activities and their material surroundings. A heuristic device is a "sensitising 'framework' for empirical research" of social phenomena [25], which conveys an image of the intricate links and feedback effects between a phenomenon's different elements and helps "identify lines of causality in related spheres" such as the design of SHTs [16].

Based on the work of Schatzki [26] and Reckwitz [27], a comfort practice is understood here in simplified terms as a bundle of activities that are part of achieving comfort and involve the consumption of heating energy. These activities are closely interwoven with the material settings by which they are co-constituted [28]. And they usually occur in the form of habitual behaviours that are learned, usually performed tacitly and are, therefore, difficult to change [29]. As a result, relatively stable patterns emerge, which are strongly related to different cultural and material contexts.

For empirical research on energy consumption, Shove [30], Gram-Hanssen [17], and others [31] have developed an understanding of practices consisting of different elements. Many case studies are then concerned with extracting these individual elements to understand how practices are reproduced or changed.

In this case study, the research focuses on the interactions between comfort practices and material arrangements more generally. On the one hand, I look at the doings that occupants perform to achieve comfort in their homes. On the other hand, I look at the material arrangements, including technologies and things [28], that enable and constrain these practices. This study draws on this main analytical distinction between material arrangements that exist and practices that happen [32] to understand how they form a nexus in which then energy consumption patterns emerge.

The concepts of material affordance [33,34], prescription [35] and prefiguration [32] all describe how material arrangements enable, configure and promote particular behaviour while constraining others. The concept of inscription has sharpened the view of the design intentions and programs that are incorporated into artificial material structures [36]. However, technologies are rarely used as designers intended, and other ideas and uses also feed back into the material shapes [37]. Technologies are appropriated [38] and domesticated [39], thereby leading to a change in their effects. In their extreme forms of non-use and rejection, it becomes evident that people need to be able to use these technologies in one way or another for them to endure. Thus, there are also practical affordances [34].

Consequently, these two sides are closely related and co-evolve with each other. It is this mutual dependence and interaction that is the main topic of this article.

2.2. Smart home technologies for space heating energy management

Smart home technologies (SHT) have in common the ability to connect building systems, actors and sensors within a communication network (ICT) to allow better control, monitoring and automation of various services [40]. This paper focuses on the service of heating energy provision for comfort in the home. While there are many more specific terms for this domain, such as (energy) intelligent buildings [41], smart home or building energy management systems [3,42], building automation and control systems [6] or occupant-centric control and operation of buildings [43], for the sake of simplicity I will refer to smart home technologies (SHT) in the following.

Following Tirado Herrero et al. [9], Strengers [44] and McIlvennie et al. [3], SHT can be roughly categorised according to two different logics, which are then often mixed in concrete applications:

2.2.1. Logic 1 – active user – passive technology

One logic can be described as a user-centred approach, emphasising control through the user and active interaction of households with building technologies. According to Strengers, users of such technologies are imagined as "efficient, technologically enabled and rational consumer[s]" [44]. They are "resource manager[s] of the home" [44] who are, by making energy visible through monitoring and feedback systems (apps and in-home displays) [45], provided with the necessary information and incentives to make better decisions, take complete control of their home and manage comfort and energy consumption efficiently [46,47].

Even though much research and technical developments have focused on educational and informational approaches to provide the

[1] Prebound effects describe the phenomenon of less heating energy consumption used than expected from design calculations prior to an energy efficiency measure. Energy performance gaps describe the oppositve effect of more energy used than expected after an energy efficiency measure. They both are indicators for the actual consumption compared to the demand from the design stage.

necessary feedback and incentives [45], these strategies seem to have led only to minor savings in energy. In a meta-study on electricity, Delmas et al. [48] only identified savings in the low single-digit percentages, a finding that, according to Buchanan et al. [49], can be applied to household energy consumption in general. It is also unlikely to change even with more innovative approaches such as gamification [50]. Apart from a lack of interest or small savings [49], such approaches generally seem unable to consider the broader social, cultural and institutional context [46].

2.2.2. Logic 2 – passive user – active technology

The second logic can be described as a system-centric approach [4]: The user has a more passive role, and technology provides comfort and reduces energy consumption on the user's behalf. The technology first monitors boundary conditions such as occupant preferences, indoor conditions, and occupancy patterns. It then uses algorithmic or third-party control to optimise energy consumption and balance the demand and supply of the broader energy system [3,43]. Examples of this approach include the integration of buildings into smart grids through demand-side management and early approaches to fully automated buildings.

Approaches to tightly controlled indoor conditions have often been criticised [51–53] for relying on a too narrow definition of comfort, neglecting building users' psychological and behavioural adaptation [54]. They have also been accused of reducing the perceived comfort when occupants lack the feeling of having control [55]. Furthermore, because the comfort range is reduced under tightly controlled conditions, the automated maintenance of these conditions has been criticised as very energy-intensive [51,56]. Conversely, variable indoor conditions, which fluctuate more with the outdoor temperature, should result in lower energy consumption and be more acceptable or even preferable to many occupants [57].

2.2.3. A blending of the logics – current approaches of SHT

Since neither approach's ultimate form seems to lead to the desired results, they are often mixed [3,43,44]. This is also reflected in the most important norm on building automation [8,58] and the Energy Performance of Building Directive. According to the latter, such technologies aim to "support energy-efficient, economical and safe operation of technical building systems through automatic controls and by facilitating the manual management" [6]. Still, high-level automation [59] and the division between a passive user and an active, control-taking SHT seem to dominate many approaches [3]. Innovative approaches to the technical monitoring of user preferences and behaviour, such as human-in-the-loop approaches [60], shall then provide a remedy to a lack of user control [43,59] and allow heterogeneity of behaviour to be predicted [61].

More recent approaches also extend the boundaries of the system. Darby refers to a system-focused narrative [4], integrating demand-side management with the volatility of renewables and district heating requirements. Buildings can store heat in the building mass and load shift demand, increasing flexibility [13,62,63]. These approaches are thought to integrate the mutual requirements of energy supply, distribution, and demand [64].

However, the question remains about how robust such systems are to heterogeneous comfort practices and spontaneously varying conditions [13,62] and how they cope with short-term adaptation requests [61]. A tension exists between the technological optimisation of building performance based on predicted user behaviour on the one hand and the user's freedom of control on the other. Another tension seems to exist between the homogeneity and uniformity created by many modern building technologies [65,66] or control approaches [13] and the heterogeneity of indoor conditions that is evident in many homes [67,68]. While homogeneity of temperatures could mean higher efficiency, heterogeneity appears to contribute physiologically to positive comfort perceptions [57].

2.3. Literature review and research gap

The aim of this study fits well within a research tradition that looks at how households use SHT, how comfort and heating practices change as a result, and how both affect the energy performance of buildings. Much of this literature focuses on the complexity of comfort practices and the wide variation in the use of SHT.

A key issue is that using SHT in everyday practices often does not match the designers' expected user behaviour. According to Wilson et al. [69], the field is too technology-driven and lacks a clear user-centred vision. Technology's integration into practices is affected by differences in competencies and engagement of individual household members [12], in preferences such as comfort, cost and value [15], and in relationships within and beyond household boundaries [12,70,71]. Occupants must learn to use these technologies and domesticate and adapt them to their needs [72]. And when new technologies challenge existing comfort practices, the unintended consequences of the evolving interactions have potential implications for energy consumption.

The difficulties arising from the need to adapt technologies to the chaotic and varied nature of residents' daily practices [69] are also reflected in what seems to be a paradox: On the one hand, households are often not sufficiently involved through control options and feedback [3], but on the other hand, many people also seem to have little interest in more control or information [44,49], corresponding to low perceived usability [40,73]. Improved feedback can lead to better engagement by supporting residents in their sense-making process [61]. However, it can also shift the focus away from energy consumption by emphasising comfort, health or other aspects [74], which is one reason for the extensive criticism of such technical approaches by Shove and colleagues [75,76].

It has also been shown that SHT can lead to changes in system behaviour due to demand side management, load shifting, and low-temperature heating, which can lead to difficulties in operation, at least for some households: Both Larsen et al. [62] and Miu et al. [61] point out that demand flexibility and load shifting do not necessarily coincide with occupants' routines and that fixed heating schedules increase the likelihood of occupants overriding default settings.

Another common theme is the delayed and slower response of low-temperature systems [61,77] or panel heating systems [13], restricting the ability of occupants to change temperatures at short notice or to rely on the sensation of warmth or feedback from hot radiators. These inertiae in system behaviour might also limit how much can be saved from lowering temperatures during short absences [59]. The above literature suggests that a change in system behaviour due to SHT upgrades may lead to practices being adapted [13], households becoming disengaged [12], or households creating workarounds to maintain their old comfort practices despite the system effects [52]. However, the consequences of the described interactions on energy performance remain a topic that has yet to be sufficiently explored through empirical research.

Overall, the main challenges for the successful use of SHT are evident: They lie in the wide variation in household practices due to the different meanings that households associate with their home [78], the range of previous experiences and knowledge of users [13,77], conflicts about comfort between household members [70], and the various material aspects of the home into which such technologies must be integrated [79].

2.3.1. Research gap

In the above-mentioned studies, several issues repeatedly emerge, which are at least partially addressed in this study. Instead of relying mainly on reported behaviour for isolated cases and metered consumption over relatively restricted periods, this study uses metered indoor temperatures and energy consumption for two complete multi-apartment blocks over two years. Furthermore, the study attempts to systematically integrate technical approaches, comfort practices and energy savings, looking at the effect on the energy performance of individual households and a building as a whole.

The case study of 137 households also has the advantage of going beyond the often relatively small sample sizes and short observation periods in many studies. The SHT examined in this study was purchased by a housing company and installed in all the apartments of the multi-apartment building. Consequently, the study has no self-selection bias for motivated or tech-savvy households, as we often see in studies where SHT is installed in households recruited explicitly for research. Most studies also tend to focus on homeowners who can carry out the necessary installations. In contrast, this study focuses on tenants in multi-apartment buildings, which are particularly relevant in Germany, where half the population lives in such buildings [80]. Because these buildings are home to people from very different backgrounds, including social housing occupants, people with little income receiving subsidies and middle-income families, there is also no bias regarding technical literacy or motivation to acquire an SHT.

Lastly, this research includes a robust analysis of the material affordance of the SHT under study. While technical literature tends to focus on technical issues such as interoperability, data security or reliability [40], social science literature tends to focus on the meanings and engagements in practices. Here, I look more specifically at the material affordances of the SHT versus the practical affordances of the users, trying to understand what is necessary for the technology to work and what is essential for the occupants to feel comfortable.

2.3.2. Research question and hypothesis

In the following section, I will investigate how households' interaction with an SHT based on multi-zone control and demand-side management affects their heating patterns and heating energy consumption. I will also analyse what this means for the energy performance of the larger building complex. The research aims to understand which aspects of comfort practices correspond to the occurrence of temperature differences. The work is thus directly linked to the developments described above. Firstly, it connects to the frequent observation of highly variable indoor temperatures within dwellings [67,68,81,82]. Secondly, based on the observed trend towards more homogeneous indoor temperatures in modern buildings [51,57,65], which is presumably also supported by certain features of SHT [13], this research addresses the question of to what extent these more homogeneous indoor temperatures could be rejected by households proactively seeking differences in temperatures.

This study investigates the hypothesis that the interplay between the homogeneity of thermal conditions created by modern building technologies and the heterogeneity created by certain comfort practices leads to problems in energy performance. It does so by comparing occupants' comfort practices with the material affordances of an SHT in a well-insulated building and those of technologies in the conventional building stock in Germany.

3. Methods and data

3.1. Description of the case study

In 2020, 137 households moved into two newly constructed multi-apartment buildings equipped with a new, not yet fully commercialised, SHT. During the last decade, this SHT has been developed in a collaboration between a University and a metering company for heat cost allocation. In a transdisciplinary research project, a living lab was set up for the first real-life test of the technology to prove its successful application and trigger learning processes and innovation. Heating energy consumption data from two almost identical buildings in the same neighbourhood and with the same construction but only 124 residential units serve as a reference value for energy savings. In this project, the task of the social scientists was to analyse interactions between occupants and technologies, their effects on energy consumption and trigger co-production with occupants. The housing association's main interest was to assess the savings in heating energy consumption and to evaluate the effort and cost involved in implementing a state-of-the-art SHT as it looks for cost-effective ways and innovative approaches to improve the energy performance of its building stock. Since its first implementation in 2020, this technology has been installed in >500 apartments of different housing associations across Germany.

All four buildings provide a mix of social housing, subsidised housing for middle-income families, and regular rentals, as is typical of large housing projects in this municipality. The tenants learned about their heating system only after moving in, so the study has no problems with the self-selection of motivated or technology-savvy residents. Still, by signing rental contracts, all tenants agreed for the monitoring data to be analysed. The case study buildings with their high-efficiency level (51.4 kWh/m^2a final heating energy demand according to the Energy Saving Ordinance [83]), while certainly not representative of the total German building stock, serve as a critical case [84] because demand-side management and load shifting should work even better in such buildings than in the majority of the building stock.

To serve as a reference case and better understand typical comfort practices in conventional multi-apartment buildings – more representative of the German building stock – the study includes the analysis of a larger sample of 251 households. These households live in buildings with relatively low insulation, gas or oil-based heating systems and classical radiators with thermostatic radiator valves (TRVs). All data sources are described in more detail below.

The operation of the analysed SHT (see Fig. 1 for a schematic diagram) corresponds to the general description of SHT given above. The technology thus combines two mechanisms: An individual room control (multi-zone control) and a connected and demand-driven regulation of the central heating unit, which correspond to the user-centred control logic and the system-centred automation logic, respectively. These features make it a typical case of SHT as studied by other authors [3,4,8,14,64,85].

Because the technology under study is an emerging technology that has not yet reached market maturity, an advantage of this living lab research project is the possibility of opening the black box of the SHT and revealing its underlying assumptions and mechanisms [86,87].

3.2. Data sources and data analysis

The analysis is based on a mixed-methods case study design [88], using quantitative and qualitative data to understand the different elements of comfort practices and material arrangements. Furthermore, informed by a socio-technical research design from Love and Cooper [89], the analysis is based on a combination of technical as well as social data and methods. It uses models on heat regulation, building physics and social behaviour, as well as data from technical devices, surveys and interviews (Table 1).

The data is first evaluated using an inductive approach, i.e., it aims to identify fundamental mechanisms of friction between material and practical affordances corresponding to higher heating energy consumption. Regression analysis is then used to systematically test the effect of temperature variations on heating energy consumption. The primary data sources are:

i. Survey data: In the spring of 2022, a survey with 30 participants (response rate of 21.9 %) in the case study buildings was conducted to analyse comfort practices with the new heating technology. The same survey questions were answered by 18 households (response rate of 14.5 %) of the two identical reference buildings with conventional heating technology. A secondary analysis of a sub-sample of a survey with 251 households is used to compare comfort practices in conventional buildings (low insulation, gas or oil-based heating and radiators). The total survey of 485 households (response rate of 8.1 %) was carried out in different building types 12/2021–01/2022, using a slightly

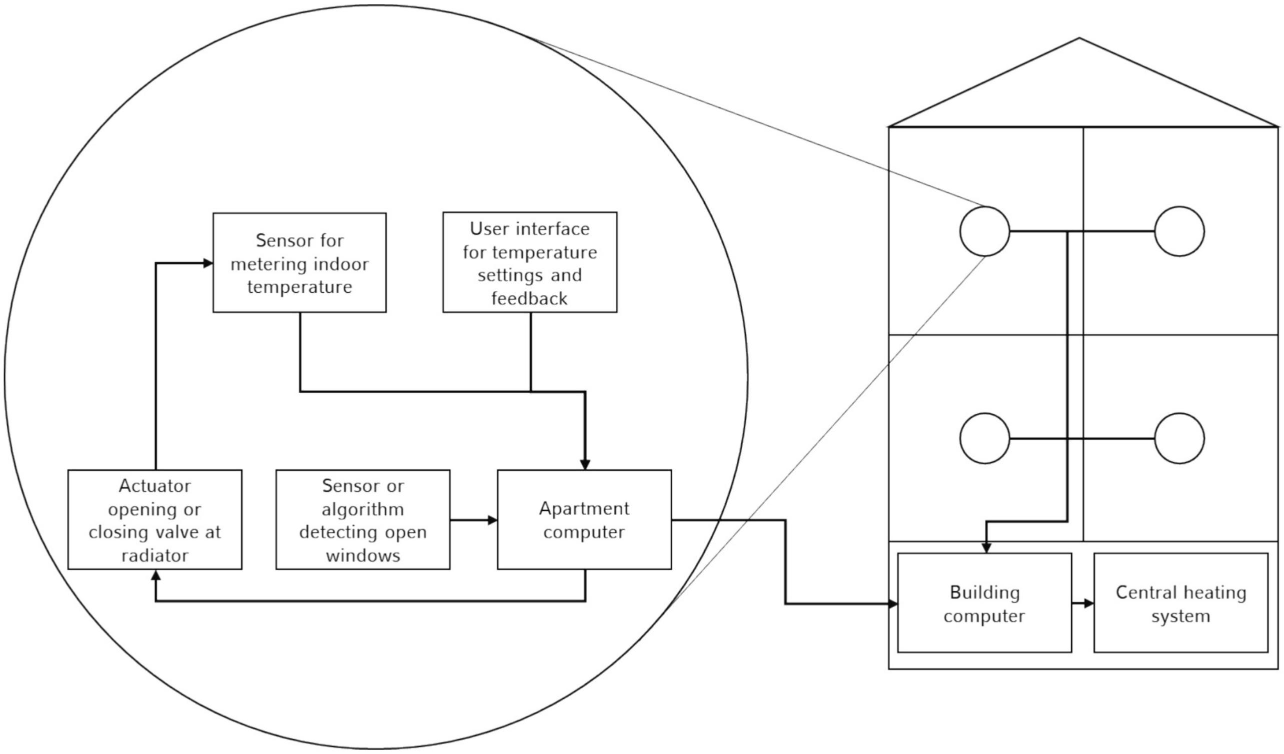

Fig. 1. Illustration of the Smart Home Technology combining features for occupant control and demand-side management.

more extensive questionnaire. Of the 485 households, 132 also agreed to have their indoor temperatures monitored in living and sleeping rooms for four weeks, giving a more detailed picture of differences in indoor temperatures in a varied building stock. All surveys included questions about demographics and household characteristics, typical behaviour related to heating energy consumption, patterns of heating regulation, and comfort preferences. The data was analysed descriptively and combined with measurement and qualitative data to identify typical cases that show the range of possible interactions between different comfort practices and the SHT, resulting in distinctive temperature and energy use patterns.

ii. Measurement data: Indoor temperatures, setpoints and heating consumption have been collected for all 137 households equipped with the SHT for the winter seasons 11/2021–02/2022 and 11/2022–02/2023. As there have been problems with the familiarisation and commissioning of the building technologies during the introductory phase of the technology, data from the first heating period is not used. For most analyses, I use the monitoring data from the heating season 2021/22 to ensure a close temporal correspondence with the survey. I use the 2022/23 data with complete information available for 122 households for the regression analysis. In the 2021/22 season, full information is only available for 102 households, and there were still problems with defective components in several households that only had been resolved afterwards.[2] Measurements are conducted by the SHT every 10 min and then directly aggregated to the hour by taking average values.

This data is used to analyse the 'behaviour' of the technology as well as households' behaviour. Two indicators are used to depict temperature variations within apartments – one for differences between rooms and one for variations during the day. The indicators have been calculated by taking the average values of the measured daily temperature differences within apartments. All variables for the regression analysis refer to the apartment level. Some descriptive statistics of the independent variables of the regression models are shown in Table 2.

iii. Qualitative data: During the project, I conducted several expert interviews: With housing associations, experts in the field of SHT, and developers of the SHT in this study. I recorded their expectations and experiences with different building technologies to better understand the SHT analysed in this study. These data were coded based on qualitative content analysis [90]. Another data source for examining the SHT and understanding the motivations, assumptions and challenges of implementing this SHT was operating instructions or notes on internal communications. Furthermore, observational and personal communication data has been collected, including notes from over 30 home visits, accompanying tradespeople when they visited households with heating problems, or from email and telephone contacts with various project stakeholders, including residents.

As is typical of case studies and ethnographic research, I used different approaches to collect data on the residents' practices and their interactions with the SHT. The challenge with the qualitative data is that it is inherently more diverse and less standardised than survey or measurement data. In this study, I use the qualitative data mainly to cross-validate and support the analysis based on the measurement and survey data. Particularly in interesting cases, such as the in-depth stories reported below, the interpretations based on the measurement data and the links between statements on individual items were checked by observations made for the same or similar households. The qualitative data thus particularly helped in the first step to discover interesting patterns and relationships between the SHT and different aspects of comfort practices. Then, the data has been used to deepen the understanding of the survey and measurement data findings. The various data sources are triangulated, i.e. they are used to substantiate each other and ensure validity [88]. The combination of measurement, survey, interview and

[2] Although the year 2022/23 was exceptional due to the energy crisis in Europe, it did not affect the results of the study (see chapter 6.2 Limitations).

Table 1
Data sources.

	Case study (energy-efficient with SHT)	Reference buildings (energy-efficient with TRVs)	Conventional buildings (energy-inefficient with TRVs)
Heating energy consumption 2021/22	51,9 kWh/m^{2}a for space heating (measured)	53,5 kWh/m^{2}a for space heating (measured)	129 kWh/m^2 for space heating (self-reported)
Buildings & building technologies	Two multi-apartment buildings, high-efficiency standard, district heat, wall-mounted radiator panels, multi-zone control and demand-side management	Two multi-apartment buildings, energy-efficient, district heat, wall-mounted radiator panels, conventional thermostatic radiator valves	Multi-apartment buildings, relatively low-efficiency standard, gas heating, wall-mounted radiator panels, conventional thermostatic radiator valves
Households	137 households	124 households	ca. 6000 households
Survey and interview data	Survey: 30 households (response rate: 21.9 %) Notes from field observations (30+ home visits + telephone calls + emails) Expert interviews with stakeholders	Survey: 18 households (response rate: 14.5 %)	Survey: 485 households (response rate: 8.1 %) Only a subsample of 253 households in buildings as described above was used.
Measurement data	06/2021–05/2023: Monthly energy consumption for space heating on apartment level; hourly indoor temperatures, setpoints and radiator temperatures on room level for all apartments (with gaps)	06/2021–05/2023: Monthly energy consumption for space heating on building level	12/2021–01/2022: Hourly indoor temperature measurements in living rooms and bedrooms of 108 households

Table 2
Descriptive statistics for independent variables in regression models for the heating period 2022/23.

	Mean	Min	Max	SD	n
Heating energy consumption Nov-Feb [kWh/m^2]	32.3	0	99.5	20.9	122
Flatsize [m^2]	72.6	43.0	140.5	22.9	122
Outside area [m^2]	79.8	27.8	267.2	48.3	122
Avg. apartment temperature Nov-Feb [°C]	20.8	13.9	25.6	1.7	122
Avg. diurnal temperature difference within the apartment Nov-Feb [°C]	3.1	1.2	5.6	0.9	122
Avg. temperature difference between rooms Nov-Feb [°C]	3.1	1.2	9.6	1.4	122

observational data helps to get a detailed picture of the differences between ideas about occupants as inscribed into technologies [35] and actual user behaviour shaped by past and current comfort practices and material settings.

4. Results

The following section describes how interactions between comfort practices and SHT affect energy consumption for space heating. The chapter is divided into six parts. 1) A short analysis of the energy savings on the building level is provided. 2) The characteristics of the material setting of conventional building technologies are briefly reviewed. 3) The material affordances of the SHT are compared to the ones of conventional buildings. 4) Typical patterns of comfort practices, as we see them in conventional energy-inefficient buildings, are discussed. 5) In-depth stories from the case study are presented to illustrate the range of possible interactions between comfort practices and the SHT. 6) Regression modelling is used to analyse the overall impact of the interaction effects between SHT and varying temperature patterns on heating energy consumption.

4.1. Energy consumption in buildings with/without SHT

Two buildings with 137 residential units were equipped with the SHT described above in December 2020. After most of the initial problems had been solved, the average climate-adjusted energy consumption for space heating in the following 2021/22 season amounted to 51.9 kWh/m^{2}a. In contrast, the climate-adjusted heating energy consumption in the two reference buildings with a conventional heating control system (TRVs) was 53.5 kWh/m^{2}a. Compared to the reference buildings, this translates into savings of approximately 6 %. Compared to the final energy demand for space heating stated in the energy performance certificate for the smart building (51.4 kWh/m^{2}a), an EPG of 1 % is observed. Thus, the building consumed about as much energy as predicted by design.[3] In the second season, 2022/23, the climate-adjusted heating energy consumption fell to 39.5 kWh/m^{2}a (EPG of −13.7 %).

The substantial reduction in energy consumption in 2022/23 can be attributed to the energy price crisis caused by Russia's invasion of Ukraine. Due to a temporary sharp increase in energy prices and the resulting uncertainty, households across Germany cut back sharply on their heating consumption for a few months [91]. Interestingly, the difference between the case study and reference buildings remained relatively constant at −7 %. This temporary effect does not affect the remaining analysis in this study.[4] In summary, despite stable savings of about 7 %, the performance of the SHT has fallen short of expectations.

4.2. Understanding the material of energy-inefficient buildings

Before analysing the interplay between SHT and comfort practices to explain the relatively low savings, it is essential to consider the case of energy-inefficient buildings first. I argue that it is the setting of energy-inefficient buildings – i.e. a material context of low insulation, high flow temperatures and manual control options – in which habits and routines of achieving comfort evolved. In energy-inefficient buildings, these practices result in heterogeneous and fluctuating temperatures. They also contribute to prebound effects, which are the opposite of energy performance gaps, namely lower heating energy consumption than expected from design predictions [20]. In contrast, in energy-efficient buildings equipped with SHT, issues arise because established comfort practices often remain unchanged, even though the material setting requires adjustments in behaviour.

Most residential buildings throughout Germany have been heated in the last decades with gas and oil-based heating systems [19], with

[3] However, the SHT was not considered within the energy demand prediction according to the Energy Performance of Building Directive, which is principally possible and would further reduce the predicted energy demand and thereby lead to a larger energy performance gap. Furthermore, heating consumption for hot water, which is not considered in this paper, amounts to about 40 kWh/m^{2}a in the case study buildings, which is much more than the calculated 22.5 kWh/m^{2}a. Because a large part of the hot water consumption can be considered dissipation losses and, therefore, internal heat gains, actual heating energy demand should be further decreased.

[4] For further discussion see Chapter 6.2 Limitations.

radiators that could easily reach 60–70 °C and then emit about half of the heat through radiation [92]. Occupants could regulate the temperature using thermostatic radiator valves (TRVs), showing numbers from one to five, with one step representing a temperature difference of 4°. Their designers constructed TRVs to show numbers instead of temperatures because the same setting can correspond to different air temperatures depending on context and because air temperatures are not the same as perceived temperatures [93,94]. Although TRVs will keep temperatures constant when kept in the same setting, a minimal adjustment can result in significant temperature jumps and increased heating activity. Occupants can then use radiators as a stable source of warmth within a room when turning up TRVs a little bit higher for some time, a behaviour Revell and Stanton [95] describe as the timer theory of thermostat use. Generally, heating systems with high flow temperatures are required to compensate for heat loss in buildings with low insulation and high heating demand, which is the case for the majority of German buildings [18,96]. Conversely, indoor temperatures will cool down relatively fast when occupants turn the heating down in such buildings. Therefore, it seems natural to change thermostat settings regularly: Keep them low in unoccupied rooms and only heat rooms when needed to avoid high heating bills. However, such a practice also favours relatively substantial temperature differences in time and space.

These findings about comfort practices, as we find them in the majority of the German building stock, are confirmed by the temperatures that have been monitored in energy-inefficient buildings as part of this study: Table 3a shows substantial spatiotemporal variations in indoor temperatures within apartments, with bedrooms being on average 5 °C cooler than living rooms with some differences during the day. The standard deviations of temperatures between apartments also provide evidence of considerable household variations.

4.3. *Understanding the material of energy-efficient buildings with SHT*

SHT in highly energy-efficient buildings changes the material setting for comfort practices described above in many ways.

4.3.1. *Material affordances of SHT*

With their SHT, occupants choose setpoint temperatures in the case study for each room via an in-home display. This multi-zone control is intended to improve occupant control and reduce what designers consider inaccurate system use, such as repeatedly adjusting settings to increase or lower indoor temperatures and using heating controls like water valves to control heat intensity [97]. The system compares each room's constantly monitored indoor temperature with its setpoint temperature. When occupants choose setpoints between 19 and 25 degrees – which is in the usually expected range for indoor comfort [98] – the system can ensure through demand-side management that all available heating surfaces are used to maintain indoor temperatures, avoiding situations where only some radiators heat large areas while others are turned off completely. By maximising heating surfaces, demand-side control can lower flow temperatures and, as a consequence, reduce dissipation losses and internal heat shifts. This makes the system more akin to a low-temperature heating system (e.g. underfloor heating), which facilitates the integration of renewable energy sources, low-temperature district heat or the electrification of the heating systems via heat pumps.

One of the developers accordingly described the system's main effect as follows:

> *"The user sets a setpoint (desired temperature), and the control then allocates heating intervals according to this setting. This is the purpose and predetermined physics of low-temperature heating control. (…) The fact that the radiators do not reach the full flow temperature (Average heating temperature around 45°C) due to short intermittent heating cycles is a sign of good optimisation and energy output with radiators that heat up as little as possible."*
>
> *(Technology Developer 1)*

Fig. 2 shows the typical behaviour of the system. It depicts the intermittent heating cycle with heating temperatures that, for most of the time, stay below 40 °C (35.2 °C on average in heating mode). Consequently, occupants can no longer use radiators as a stable source of warmth within a room as they were used to in conventional buildings. According to a technology developer, this "*lack of radiant heat is a known side effect of the smart home technology*" (Technology Developer 2). Particularly in the period after moving in, many occupants noticed that they missed the feeling of a hot radiator. Another developer regularly mentioned the "*common perception problems*" (Technology Developer 1), where occupants confuse the desire for a warm room with the desire for a warm radiator. While the SHT designers see only the former as a system purpose, many residents, especially at the beginning of the project, seemed to expect the latter as well. Presented with the item "I find it important to be able to feel the warmth of the radiators directly", 8 of 26 occupants (31 %) in the case study buildings tended to agree (4 or 5 on a 5-point Likert scale), while in the survey of households within conventional buildings, almost 60 % tended to agree with this question. This indicates that a considerable share of the occupants value the warmth or cosiness felt from a noticeable heat source within a room, in line with the findings of Devine-Wright et al. [99]. The differences between the surveys could also be evidence that such valuations might change when material elements change, but this may not apply equally to all households.

Another effect of reduced heating temperatures is the system's reduced and delayed response to setpoint changes. Because of the slow reaction speed and because the *"[system] regulation decides for itself and energy-saving reasons also quite slowly, when and how often additional heating is required"* (Technology Developer 1), occupants are left with little short-term control to adjust indoor conditions. As one occupant commented in the survey: "*(…) the system works very well. You just have to know that if you set the temperature higher, it takes a while!"*

From the designers' point of view, occupants should have little reason to interact with the heating system once they have found their preferred settings. Because of low temperatures and intermittent heating, radiators fall out as a predictable source of heat over which occupants have control. The reduced reaction to setpoint changes and

Table 3
a (on the left): Measured indoor temperatures in living rooms and bedrooms (mean and standard deviation (SD)) from temperature loggers in the broader household survey ($n = 109$) and b (on the right): setpoints and indoor temperatures in living rooms and bedrooms in the case study ($n = 137$).

Conventionally heated buildings (Energy-inefficient buildings)			Case study (Energy-efficient buildings with SHT)		
	Living room	Bedroom		Living room	Bedroom
Avg. Indoor temperature [°C]	20.69	16.43	Avg. Indoor temperature [°C]	21.86	20.74
Avg. SD of diurnal indoor temperatures within rooms [°C]	1,15	1,23	Avg. SD of diurnal indoor temperatures within rooms [°C]	1,41	1,39
SD of indoor temperatures between apartments [°C]	1.76	1.15	SD of indoor temperatures between apartments [°C]	1.40	1.70
			Avg. Setpoint daytime [°C]	19.19	16.48
			SD setpoint daytime between apartments [°C]	3.42	3.06
n	106	109	n	123	123

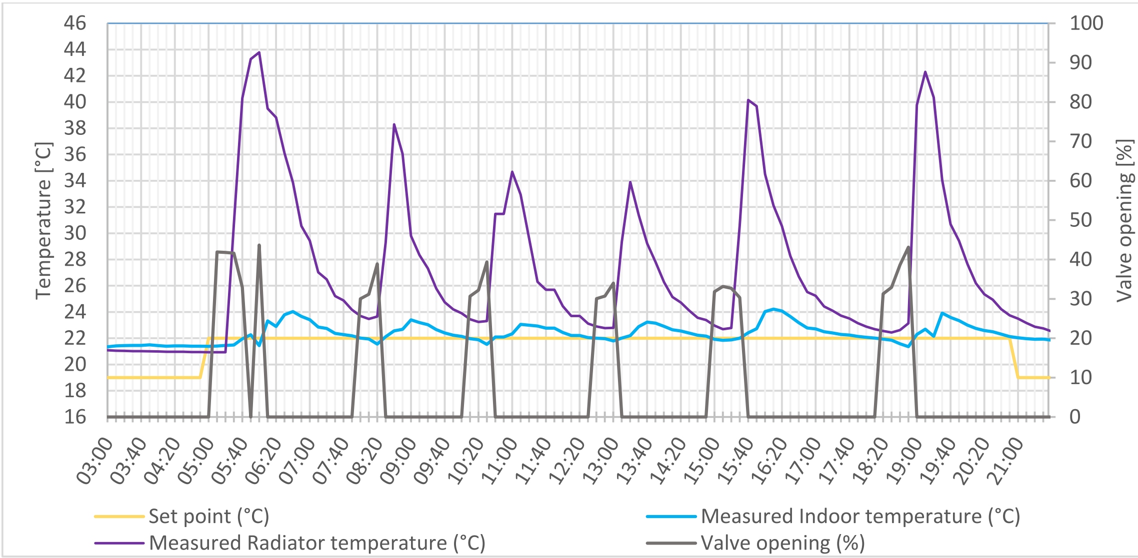

Fig. 2. Typical view of the monitoring for one room, showing setpoints, metered room and radiator temperatures, and valve opening.

prolonged preheating periods is also typical for low-temperature heating systems [61]. It also limits the use of temperature setbacks when rooms are unoccupied for shorter times. In contrast, occupants expecting the radiator to heat a room quickly when turning up the setpoints will be disappointed, leading some to complain heavily after moving in.

4.3.2. Problems with measured air temperatures

Another issue related to the lack of control over radiators is that perceived and air temperatures are not the same but differ depending on the context [100]. Research has shown that air temperatures are only a good indicator of perceived temperature if there are no radiant asymmetries from colder or warmer surfaces [94,101]. Thus, rooms must be heated evenly, and the thermal mass must be kept close to the desired temperature to ensure that the perceived temperatures correspond to the measured air temperatures. In contrast, if rooms have been cooled down a lot, air temperatures measured shortly after a heating cycle are not a good indicator for perceived temperatures.

However, as Fig. 2 shows, indoor air temperatures are the sole control parameter for the SHT. Therefore, occupants and technical staff may be tempted to judge indoor conditions based on this information alone. There were several instances where technical staff and occupants argued about whether rooms were well heated, with both sides referring to temperatures as evidence for their arguments. In an email forwarded by a housing representative to a technical project employee, an occupant complained about the heating not working correctly: "*The radiators can definitely not be controlled manually; they do what they want; we have no control over the radiators! It's bitterly cold in some rooms and warm in others! It can't go on like this!" (Occupant 1)* A technical staff member provided a list of average room temperatures from the monitoring, explaining to the housing representative: "*Here are the current room temperatures as a snapshot. The temperature in the apartment is very high, about 23°C on average. It is possible that the temperature in the bathroom and bedroom (attached) appears virtually and temporarily a little too high because the radiators may be somewhat blocked (covered with textiles or blocked with furniture). The corridor cannot quickly cool down to 21°C in such a highly insulated building when 4/5 of the other rooms are conditioned to >23°C. The apartment is warm, just as the occupants have requested.*" This quote shows that it can be tempting, even for technically educated staff, to only look at air temperatures, neglecting other possible sources of concern, such as radiant asymmetries or a lack of sensory feedback from radiators. The quote also highlights the potential for other sources of error to influence the accuracy of temperature measurements. These may include misaligned or obstructed measuring devices, demonstrating the need for a certain level of technical expertise to identify such sources of error. Such subtleties of the sense-making process in the use of environmental parameters have also been well illustrated before [74]. In this study, conflicts regarding the accuracy of the recorded room temperatures appeared regularly. While the technical staff usually advised occupants to leave setpoints at higher levels when feeling too cold, many were reluctant to do so for fear of high heating expenses and expecting the shown temperatures to reflect actual thermal indoor conditions.

4.3.3. Heating patterns in buildings with SHT

The analysis of the monitoring data shows that indoor temperatures are, on average, much more homogeneous, with minor differences between living rooms and bedrooms, in the case study buildings (Table 3b) compared to the energy-inefficient buildings (Table 3a). SHT, in combination with insulation, leads to harmonising indoor temperatures despite multi-zone control. Load-shifting demand and strong insulation ($U = 0{,}43$) work well together. However, the standard deviation of average temperatures over households, particularly in bedrooms, and the differences between average setpoints and average measured temperatures (Table 3b) is the first indication that not all households necessarily welcome homogeneous heating patterns. Instead, this pattern suggests that occupants value and act towards differences in thermal conditions, which is consistent with previous research [67,68,81].

In summary, the analysis shows that the SHT does not support short-term changes to indoor conditions. Instead, the system smoothes indoor temperatures and the heat stored in the thermal mass, consistent with the insulation of the building envelope and the idea of demand-side management.

The system behaviour also aligns with the concept of smart grid integration, which involves smoothing the heating supply, cutting peak loads, and shifting heating loads. For occupants, the consequence is a trade-off between the efficiency gained from smoothing the heating supply and the possibility of spontaneously adjusting the indoor environment on demand.

4.4. Understanding comfort practices in energy-inefficient vs. smart buildings

Having analysed the material aspect of the SHT and its tendency to favour uniformity of indoor conditions, the next step is to investigate how certain aspects of comfort practices that have evolved in the conventional building stock lead occupants to expect variety in thermal indoor conditions.

From self-reported assessments (Fig. 3), we see that about three-fourths of all respondents in the energy-inefficient buildings at least partly agree with the statement that they appreciate different temperatures between rooms. Even though the share in the case study buildings is lower, it is still almost half of all households. This finding also suggests that the homogeneous indoor patterns observed above could result from the homogenisation of indoor temperatures not intentionally brought about by occupants. Looking at subjective perceptions of differences, occupants in the survey of energy-inefficient buildings tend to agree more often that there are differences in indoor temperatures between rooms and that temperatures fluctuate within the apartment throughout the day. However, many occupants also experience such differences in the case study buildings. Regarding the overall indoor climate, the groups' approval rates do not differ considerably.

When it comes to the assessment of the heating system, the approval rates show that, on average, after a year of living with the SHT, occupants seem to handle the technology quite well and do not seem to have any more problems with the SHT than other people have with the conventional systems.

In conclusion, the less-than-expected energy savings do not seem to be due to general issues in user experience. In contrast, occupants appear to be satisfied with the new heating technology and the indoor conditions it provides. As shown below, this does not mean that some households experience problems.

4.4.1. *Thermal variety with conventional heating*

I identify three typical patterns of comfort practices that favour differences in thermal indoor conditions. First, occupants have typical ideas (mental models [95]) about how to use building controls to save energy, which, coming from energy-inefficient buildings, favour variations in indoor conditions. Second, and related to the first point, occupants expect fast feedback when interacting with building controls such as the heating system. These interactions intensify short and long-term differences within apartments. Third, some ventilation and cooling habits might be less problematic in older buildings than in newer ones.

From living in conventional buildings with insufficient insulation and high flow temperatures, most occupants are used to turning the heating on and off to manage heating consumption and costs. In their subjective assessment, about three-fourths of the households in the energy-inefficient buildings at least partly agree that their buildings need much energy for heating (Fig. 4), which corresponds to an average self-reported energy consumption for space heating of 129 kWh/m^{2}a (SD: 71 kWh/m^{2}a). Still, the same share of households is at least partly convinced that they have effective control over their heating energy consumption.

The other statements in Fig. 4 show why this might be the case and how occupants typically take control of their heating consumption. 64 % report turning the heating off in unused rooms, and 80 % turn the heating down at night. This is supported by their ideas about how the heating works and how best to save energy: 50 % agree that keeping the heating at low levels and turning it up when feeling cold only will save most energy. Turning the heating down will not have negative consequences on thermal comfort only when occupants can expect vice versa fast feedback from their systems when feeling cold. Accordingly, 46 % of the occupants believe that turning the TRV to a higher setting will heat rooms faster, a belief that Goodhew et al. [102] called the warmer-faster model of heating.

Another indicator of residents being used to changing indoor thermal conditions on the fly with fast feedback expected is their typical reaction when feeling cold and hot (Fig. 5). While 41 % of the residents in conventional buildings report putting on something warmer as their

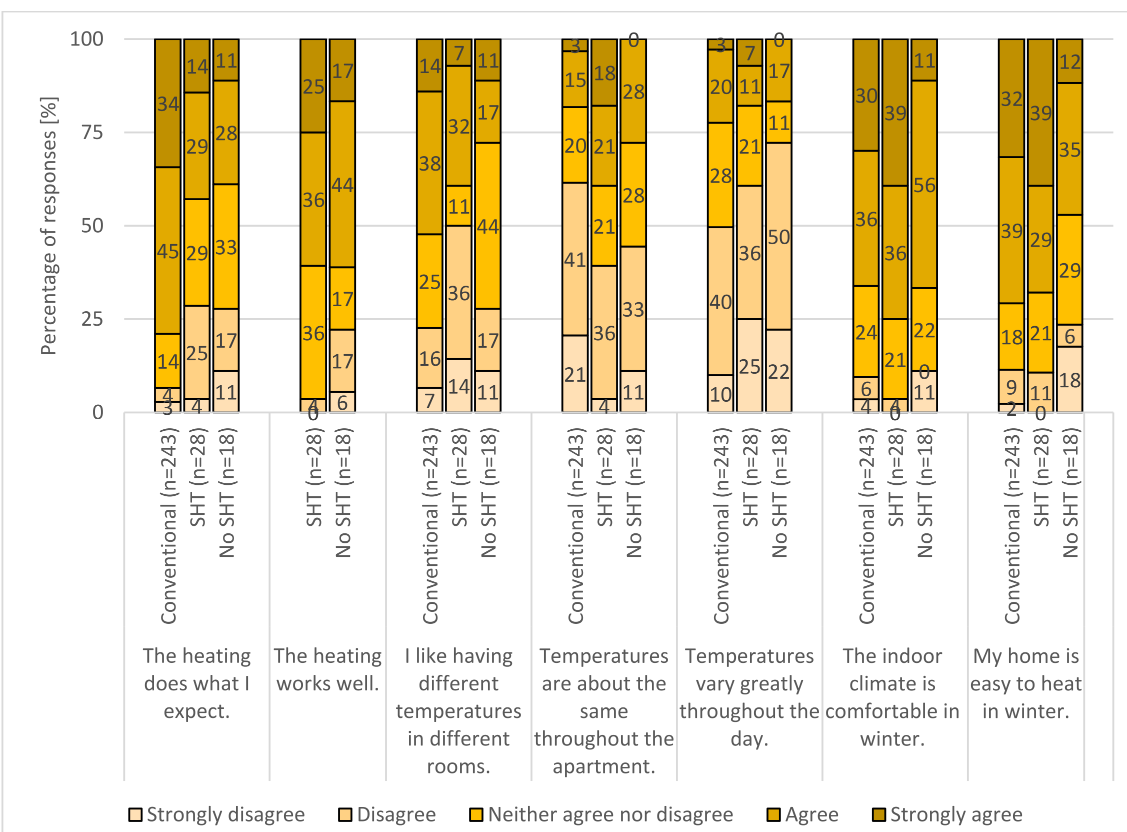

Fig. 3. Subjective assessments of the experiences with heating systems in energy-inefficient buildings (Conventional), in the energy-efficient case study buildings with SHT (SHT) and the energy-efficient reference buildings without SHT (no SHT).

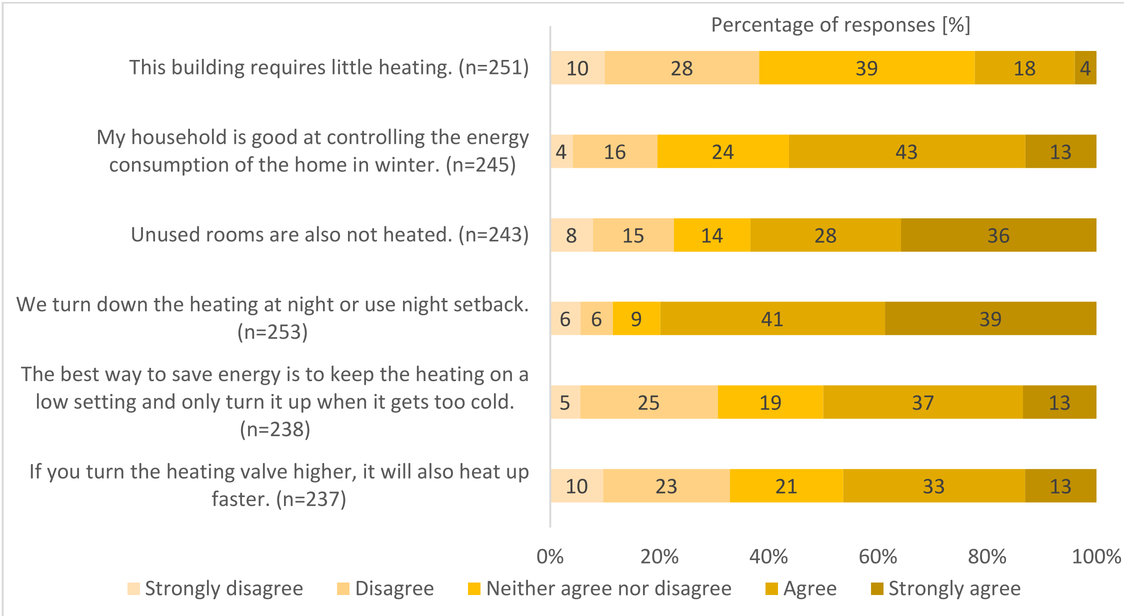

Fig. 4. Ideas about using building controls to save energy (Mental models of heating) in energy-inefficient buildings.

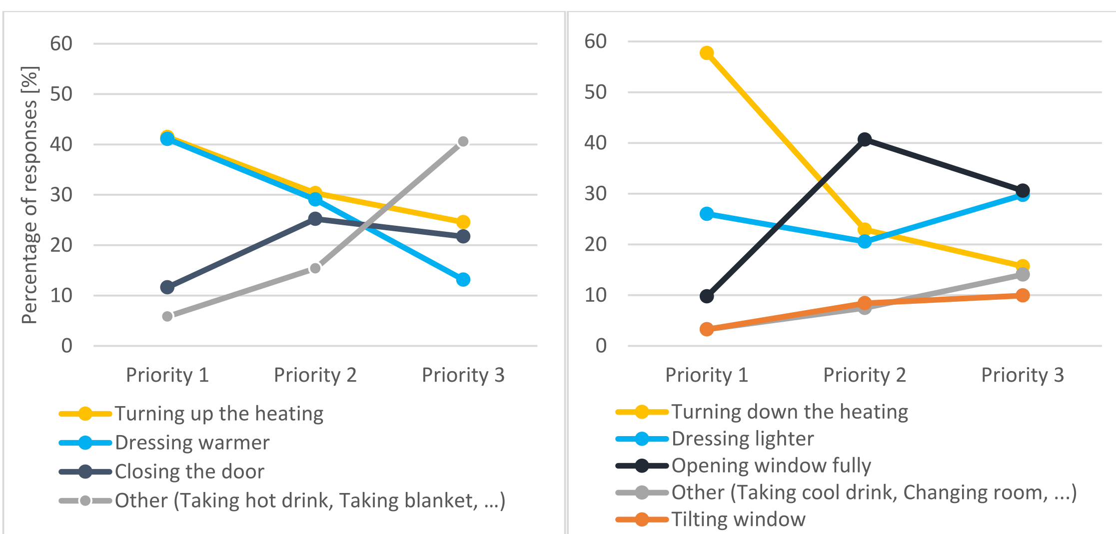

Fig. 5. a (Left side): Self-reported predominant reaction when feeling too cold ($n = 258$) and b (Right side): when feeling too warm ($n = 246$) in energy-inefficient buildings.

preferred action when feeling cold, another 41 % prioritise turning the heating on. Only 17 % of the respondents opt for another first reaction, such as closing the door, taking a blanket, or preparing a hot water bottle. Keeping the TRV setting low most of the time and turning it up only when a room needs to be warmed will only work with heaters that heat up fast and can raise the indoor temperature quickly. Although this is not the use of TRVs as intended by their designers, Kempton [97] has shown that using radiators like water valves can save energy compared to keeping them in the same setting all the time. Comfort can be achieved by feedback from hot radiators without having to raise the whole building mass to the preferred indoor temperature level. People often expect this rapid feedback when they turn up radiators when they feel cold. The equivalent response is for an occupant to open the window when they feel warm. Although this increases energy consumption, it is not an atypical reaction. It supports the argument that occupants are used to expecting fast feedback when interacting with building controls.

Self-reported thermostat settings (Fig. 6) illustrate what occupants specifically mean when they report adjusting the heating, whether by increasing or decreasing it, or by maintaining different settings across rooms. About half of the occupants report keeping their thermostats at the same level almost all the time but with different settings in different rooms. The other half reports different levels at different times and in different rooms. They also change settings in the living room during the night and when occupants are present during the day. This corresponds to the temperature differences observed in Table 2a.

Keeping doors closed is one important strategy to avoid wasting energy in differently heated apartments. From the measured (Table 2b) and reported (Fig. 7) differences between rooms, we can see that most occupants seem to have internalised this idea, with the largest share of households keeping doors to little heated bedrooms and well-heated living rooms closed. In sparsely insulated buildings, the resulting differences in indoor temperatures will also be a constant reminder to close

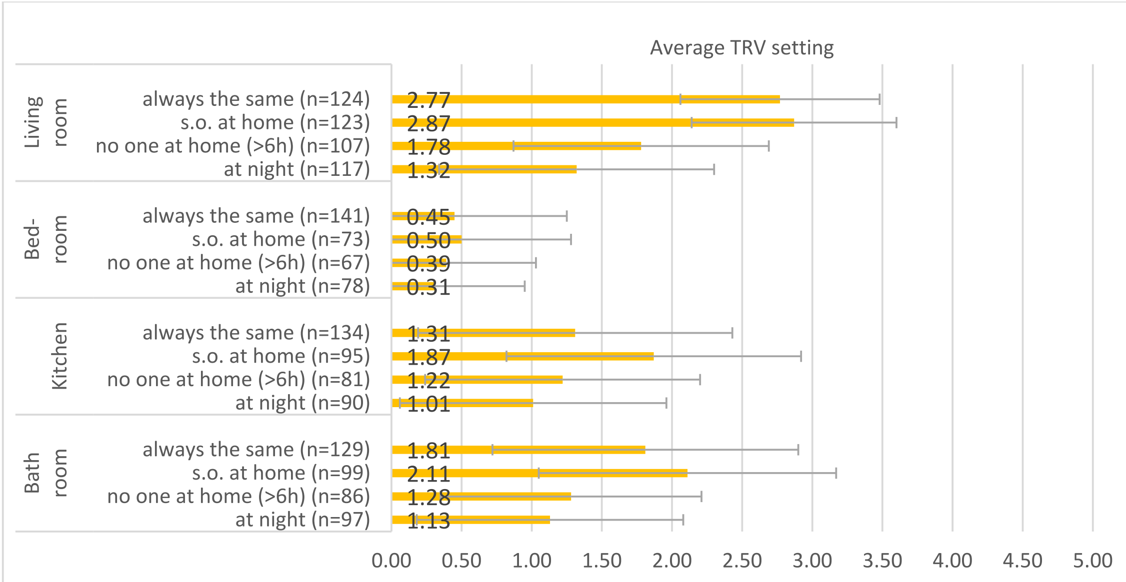

Fig. 6. Means of thermostatic radiator valve (TRV) settings (Bars) by room and occupancy pattern in energy-inefficient buildings. Distribution across households in standard deviations (Lines).

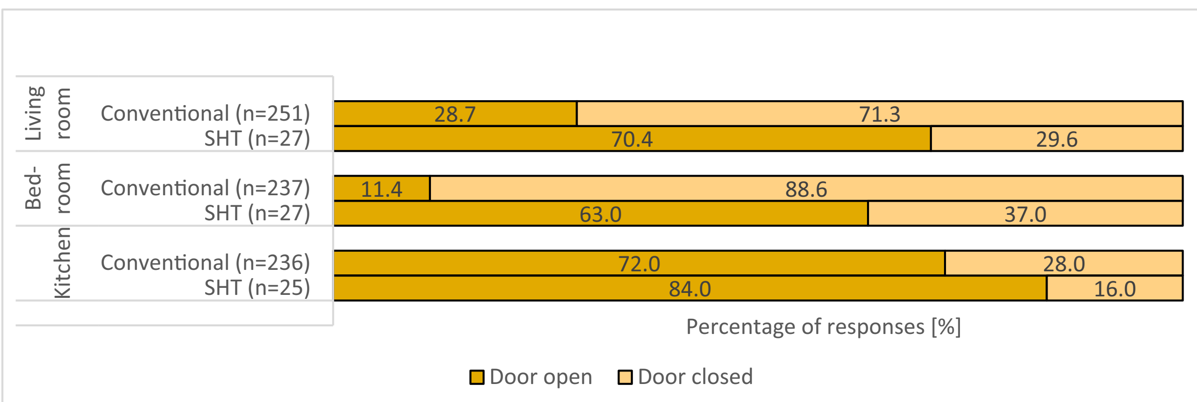

Fig. 7. Percent of self-reported door opening behaviour in energy-inefficient buildings vs case study buildings with SHT.

doors.

Keeping temperatures low and only heat when needed seems a practice so widespread that many representatives of housing companies in my interviews complained about their tenants turning the heating down too far, thereby increasing the risk of damaging the building through moisture and mould: *"The urge to save energy often leads people to heat their homes incorrectly. So in the belief of saving energy, the heaters are turned off, or entire rooms are not heated." (Housing representative 11).*

However, the belief that energy can be saved by keeping rooms principally at different temperatures and low temperatures in times of non-use is firmly institutionalised and permanently reproduced in almost any energy-saving advice. On the website of the German Environment Agency [103], for example, it is recommended that heating be turned down and different temperatures maintained to save energy. According to them, the temperature in living and workrooms can be lowered by 4 to 5° at night. Similar energy-saving advice can not only be found on most German public websites, such as the most widely known German Consumer's Association [104], but also internationally [105]: *"Make sure your heating is only on when you need it. A timer or programmer lets you set what time your central heating is on. You can save energy by setting your heating to only be on when you need it."* Suggestions such as keeping bedrooms at lower temperatures (16–18 °C) [106] serve residents as an anchor and rationale for what is reasonable to do, and it can indeed save energy in old buildings.

While in conventional buildings, energy saving is an important reason to keep thermostats in bedrooms or unoccupied rooms low, over time, different thermal conditions can also become valued for themselves. Particularly for sleeping, many occupants mentioned that they sleep better if the room is cold and, therefore, have their windows tilted. Thus, they are not only concerned about indoor air quality – a worry that might be relatively unfounded, particularly in older buildings where windows and facades are not tightly sealed – but like it cold. Keeping windows tilted seems widespread in old buildings, with more than half of all respondents saying that they prefer to sleep with tilted windows even during cold weather in winter. Moreover, of all multi-person households, >60 % of the respondents stated that someone in their household usually sleeps with an open or tilted window (Fig. 8). Although tilting windows at night will increase energy consumption, e.g. by increasing internal heat shifts [107], the impact may be less if these rooms are also not heated during the day, doors are kept closed at all times, and other rooms are only heated up when occupied.

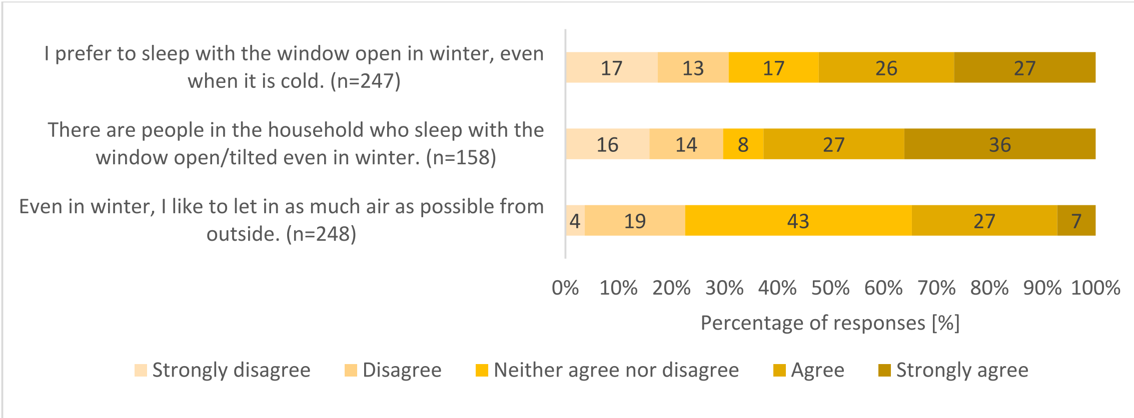

Fig. 8. Self-reported window opening practices and preferences for air exchange in energy-inefficient buildings.

4.5. *Thermal variety and SHT – in-depth stories*

So far, it has been shown that acquired routines and habits in the material setting of older, gas- and oil-heated and less-insulated buildings lead many occupants to expect variations in indoor temperatures within their homes. Furthermore, people are likely to associate this temperature variety with energy savings. These different comfort practices, on average, seemed to have worked quite well in the material settings of older buildings. The associated energy savings are indicated by the prebound effects [108].

In contrast, the following analysis shows that interaction problems can occur if these comfort practices are transferred to buildings with demand-side management and high insulation, leading to a homogenisation of thermal indoor conditions. While most households' comfort practices seem to align well with the material arrangements, some households retain their old practices in the new material settings, unaware of the consequences for energy consumption.

The following in-depth depiction of four smart building households shows the range of possible scenarios. I first show two households where comfort practices and material affordances seem to correspond well. Table 4 shows key indicators such as specific heating energy consumption or average indoor temperature for all four households.

4.5.1. *Household A – thermal uniformity at a high level*

A first example of a household whose comfort practices seem to match the building technologies quite well is Household A, a one-person household in a 43 m^2 one-room apartment located in the middle of the building and surrounded by other apartments. A distinctive characteristic of this household is the presence of tropical animals, which, according to the tenant, need constant temperatures around 22 °C day and night. Therefore, the resident had the smart home provider deactivate the night setback in her apartment, which would have lowered the setpoints in all rooms by 3°. Although she thinks the SHT is modern in a positive way, the most important thing for her is that the heating works.

During a visit in the autumn of 2022, the in-home display had been placed behind a shelf and some decorations, which suggests that she does not change the settings very often. Fig. 9 shows the heating pattern for four days. Temperatures remain relatively stable, with setpoint changes mainly resulting from the system detecting open windows and switching to frost protection. Over the heating period, indoor temperatures average around 22.5 °C.

From the designers' perspective, this heating control behaviour is desirable except for the missing night setback: The occupant has found her preferred temperature and interacted little with the system afterwards. The monitoring data show that the energy consumption is similar to that of the average household. However, the average indoor temperature is 22.7 °C and, therefore, well above the average indoor temperature of the building (21.5 °C). Although this household keeps temperatures constant – aligning with the materiality of the building technologies – they are at relatively high levels, which could point to both a habituation and a rebound effect.

4.5.2. *Household B – thermal uniformity at a low level*

Household B provides another example of a very homogeneous heating pattern. The tenant is relatively young, fully employed, and usually not home all day. She lives in a two-room apartment with a small balcony. While she is relatively satisfied with the indoor thermal conditions, she does not think the system works well. One reason is that she gained the impression that the algorithm for detecting open windows is not very accurate. Another reason is that she considers the system too complex for most of the tenants, which she has explained in an open comment: *"I'm pretty sure many tenants here don't understand how the heating system works. Many of my neighbours have a migration background and can't cope with lengthy explanatory texts. (…) Unfortunately, the window-open detection system doesn't work properly. After about five minutes, the heating switches back to heating mode, even though the window is still fully open."* However, she herself seems to cope quite well with the system.

Table 4
Table with flat size and indicators for temperature and heating energy consumption patterns in four sample households and the average household in the case study buildings (heating period 2021/22).

	Household A	Household B	Household C	Household D	Average household (of all 137)
Flatsize [m^2]	43	51	51	56	72
Space heating energy demand [kWh/m^{2}a]	35.3	54.7	48.8	49.9	51.4
Space heating energy consumption [kWh/m^{2}a]	53.5	21.2	72.6	71.8	53.5
Avg. apartment temperature Nov-Feb [°C]	22.8	20.7	19.5	19.3	21.5
Avg. apartment setpoint Nov-Feb [°C]	21.8	19.4	17.6	17.8	17.3
Avg. measured indoor temperature living room Nov-Feb [°C]	23.1	20.9	21.2	18.9	21.9
Avg. measured indoor temperature bedroom Nov-Feb [°C]	–	20.4	13.9	18.0	20.7
Avg. diurnal temperature difference within the apartment Nov-Feb [°C]	3.9	3.2	2.8	4.1	3.3
Avg. temperature difference between rooms Nov-Feb [°C]	1.3	1.2	8.5	3.0	3.1

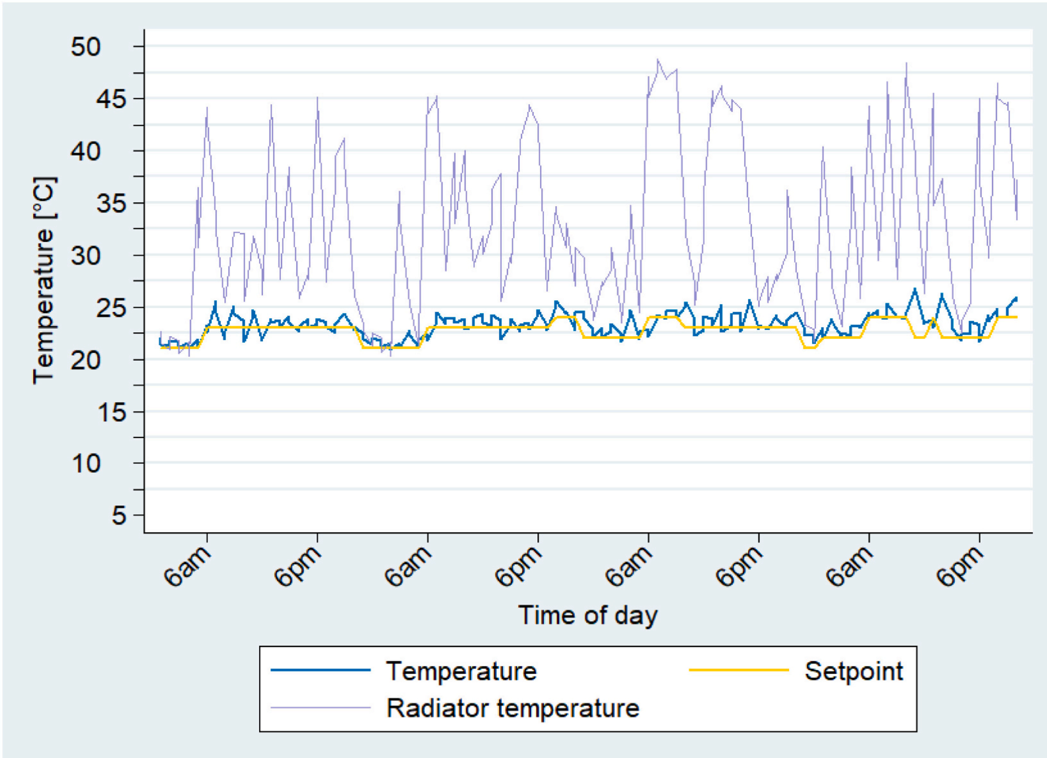

Fig. 9. Measured setpoint and indoor temperature for household A (bedroom) during four days in January with a preference for uniform indoor conditions.

Even though she stated in the survey that she likes differences between rooms and agrees that temperatures differ within the apartment, the monitoring data shows that the differences are relatively small compared to other households (1.2 °C). An obvious explanation is that doors in the apartment usually stay open. She also opens windows only briefly for shock ventilation, probably because she also cares about saving energy. With an average indoor temperature of 20.7 °C and relatively little fluctuations within the apartment (Table 4), this apartment needs only 21 kWh/m^2 for the heating season.

This case demonstrates that temperatures generally fluctuate little if occupants do not seek differences or feel the need to air their apartment excessively. Occupants can also keep energy consumption low if they keep setpoints at lower levels. Thus, energy-efficient buildings combined with such comfort practices would principally support the idea of load-shifting from SHT.

4.5.3. *Household C – thermal variety between rooms*

However, not all comfort practices match this material setting. The single Household C shares many characteristics with Household B, being relatively young, being out of home all day because of work and living in a two-room apartment. However, unlike Household B, the tenant smokes on the balcony, shares his flat with a four-legged friend, and ventilates heavily by tilting windows for long durations. Consequently, Household C differs heavily from Household B in the ensuing temperature patterns and heating consumption (Table 4).

Household C is also not very happy with the heating system. He thinks the system reacts rather slowly and does not do what he expects. In an open comment, he explained: "*The heating cannot be controlled precisely; if you turn it to level 3 and it gets cooler outside, it changes or switches off, i.e. it shows that it is on level 3, but the radiator itself is ice cold.*" In this quote, he is probably referring to the intermittent heating cycles that reduce the feedback from the radiators, which he also stated does not get warm enough. Several households have been confused by this heating pattern because, unlike conventional TRVs, the SHT decides when to turn it on, leaving little opportunity for residents to control the heat flow. Although the occupant from Household C says that the temperatures within the apartment differ, and this is what he prefers, he usually leaves the doors open between rooms. This is probably because of his pet, as the survey data show that households with cats or dogs are much more likely to keep doors open between rooms. Furthermore, he prefers to sleep with windows tilted, and he keeps windows tilted in the bedroom and living room all day.

The monitoring data clearly shows that, while the average temperature in the home is relatively moderate (19.6 °C), there are significant variations between rooms. While the setpoint in the bedroom is always on frost protection (7 °C), it averages 21.2 °C in the living room. The resulting measured indoor temperatures are 21 °C in the living room and 13.9 °C in the bedroom. However, the average indoor temperature does not fluctuate much during the day. These patterns explain the high energy consumption of 72 kWh/m^2 for the whole season.

Although both Households C and B feel that the air in their home is often too sticky, they deal with it differently.

4.5.4. *Household D – thermal variety during the day*

Lastly, Household D prefers temperature variations throughout the day. While this is a two-person household in a 52m^2 apartment, each resident has a room, which they use for sleeping and living, with doors within the apartment usually closed. Because one tenant has relatively consistent and moderate temperatures and does not heat most of the time, I here concentrate on the comfort practice of the other resident. She describes herself as someone who generally feels hot quickly and needs varying indoor conditions depending on activity.

When I first spoke to her in the middle of the winter, she mentioned her concerns about her room overheating in the summer. However, she is confused by the intermittent heating and misses the feeling of a constantly warm radiator. Favouring the room to be warm when awake, she notices that the apartment does not cool down quickly when the heating is turned off but retains the warmth for a long time. This poses a problem because she likes to sleep in an ice-cold room under a thick duvet. Therefore, she fully opens or tilts her window when sleeping, even with heavy frost outside. These descriptions are confirmed when looking at a four-day period when it has had minus degrees outside (Fig. 10). The setpoint temperatures have been regularly set to frost protection, and the room has cooled down quite heavily, sometimes to 15 °C. For the rest of the day, the heating system has to work continuously to bring the building envelope's thermal mass, which has given up much of its energy, back up to the required temperatures.

Even though she has mentioned the importance of keeping energy costs low and has said that she will most of the time not choose the highest settings so as not to waste energy, a look at the apartments' temperatures and heating energy consumption and the comparison to the average of all 137 apartments shows an interesting combination: The apartment needs almost 50 % more heating than the average household, even though the actual average indoor temperature is 2.2 °C lower. Here, high fluctuations in the one room seem to correspond to increased energy consumption.

The four in-depth depictions show how variations in the interactions between occupants and the material settings of their homes can lead to significant differences in heating energy consumption. Average indoor temperatures for the whole apartment alone are not only a weak indicator of what happens in a home – in line with what Marszal-Pomianowska et al. [67] have shown – but also a weak indicator of energy consumption. This is confirmed in the next chapter for the whole sample of smart households in the case study.

4.6. Interaction between thermal variety and SHT – regression analysis

Stepwise multivariate regression analysis with the main metering variables from the case study is conducted in the following subsection. It analyses more systematically the correlation between heating energy consumption and differences in heating patterns (Table 5). The temperature patterns are treated as indicators for different interactions between comfort practices and the material setting. The main explanatory variables are: First, the average temperature level; second, the average temperature differences within dwellings during the day; and third, the

Table 5
OLS stepwise regression for 118 apartments (with complete monitoring data available) over the heating period (Nov- Feb). T-Statistics in parentheses and *p*-values as stars (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

	(Model 1)	(Model 2)	(Model 3)	(Model 4)
	kWh/m^2	kWh/m^2	kWh/m^2	kWh/m^2
Flatsize [m^2]	−0.017	−0.108	−0.139	−0.184*
	(−0.17)	(−1.21)	(−1.55)	(−2.06)
Outside area [m^2]	0.208*	0.224**	0.236**	0.216*
	(2.43)	(2.99)	(2.77)	(2.44)
Avg. apartment temperature [°C]		0.552***	0.452***	0.509***
		(7.39)	(6.48)	(7.06)
Avg. diurnal temperature difference within the apartment [°C]			0.339***	0.281***
			(3.77)	(3.43)
Avg. temperature difference between rooms [°C]				0.208*
				(2.35)
Obs.	118	118	118	118
Adjusted R^2	0.022	0.320	0.421	0.453

average differences between rooms. All models control for dwelling size and external area as the main differences in building physics. The results confirm that larger variability in thermal indoor conditions corresponds to higher heating energy consumption in a material setting of high insulation and load shifting from demand-side management.

The high variance in the heating consumption between apartments cannot be explained by living space and external area alone (Model 1). In this building, differences in building physics between apartments are entirely obscured by the variation of comfort practices in these apartments. In contrast, temperature level has a clear and significant effect, explaining nearly a third of the total variation (Model 2). As expected, the warmer the dwelling, the higher the energy consumption. However, consistently higher temperatures are less energy-intensive than higher temperatures with large fluctuations. Trying to achieve temperature differences during the day (Model 3) and keeping differences between

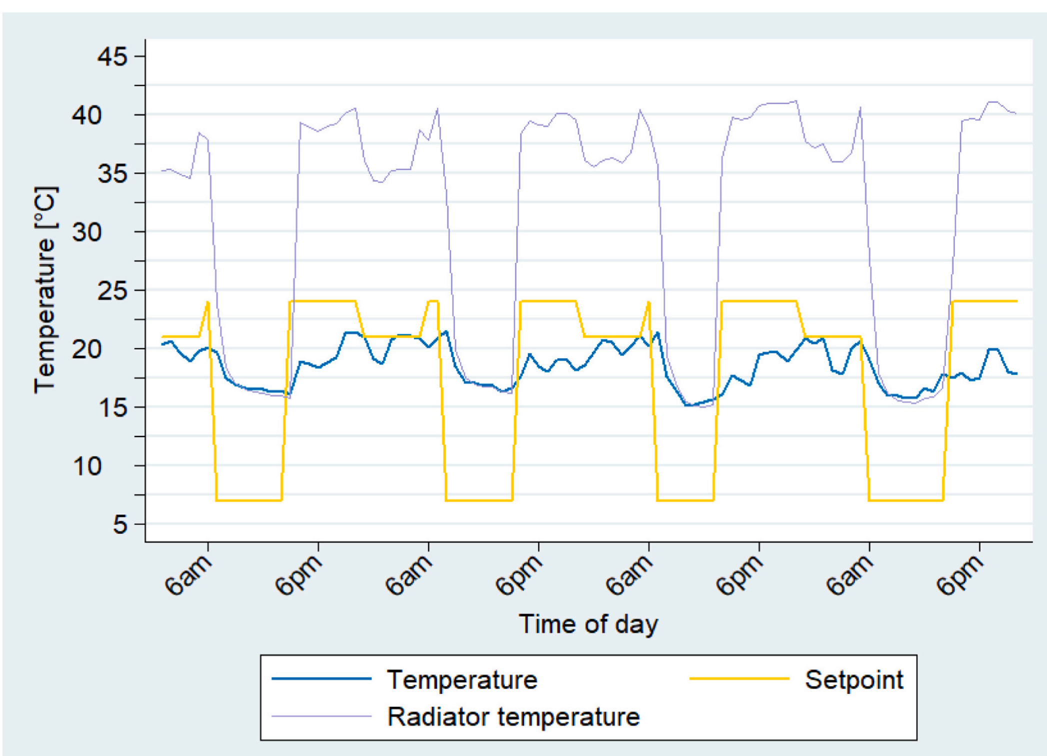

Fig. 10. Measured setpoint and indoor temperature for Household C (bedroom) over four days in January with a preference for high variation in indoor conditions.

rooms (Model 4) will lead to higher energy consumption, even if the overall temperature is constant. One explanation is internal heat shifts between rooms, particularly when doors are open. By contrast, if occupants set realistic setpoint temperatures between 18 and 25° in all rooms, the demand-side management would ensure that all available heating surfaces are used to keep the temperature level rather than one or two radiators heating the whole apartment.

The findings show that higher temperature differences correspond to increased heating energy consumption for the same average apartment temperature. Thus, buildings favouring uniform temperatures because of high insulation and SHT with demand-side management and temperature differences do not align well.

Conversely, more homogeneous temperatures align well with the SHT's idea for reducing heating energy consumption. In highly insulated buildings, occupants must actively release stored heating energy by opening windows to enjoy temperature differences indoors. The building's thermal mass acts as a buffer for changes in internal temperature and, therefore, must be actively cooled. Internal heat transfers between rooms and apartments further counteract differences in indoor temperatures [107,109]. When rooms need to be heated, the whole building mass must be brought to a new level. As the SHT is designed to save energy by reducing flow temperatures and load-shift demand, this reduces direct feedback from hot radiators and extends the time it takes to heat a room. As a result, these systems work towards relatively homogeneous temperatures – something that has been pointed out in previous research [13,59,67]. This also results in a trade-off between the energy saved by not heating or cooling on the one hand and the time and energy needed to return to a higher setpoint in a later period on the other hand.

Even though highly insulated buildings and SHT for demand-side management should fit well together, the heterogeneity of comfort practices in large multi-apartment buildings can substantially reduce the overall savings.

In a less insulated building, the effect of temperature changes is much less problematic because the indoor temperature drops much faster when the heating is turned off, reducing the energy that can be saved by keeping the thermal mass at a constant temperature. Therefore, such an environment contributes to the fluctuation of indoor temperatures and helps the occupants experience thermal variety.

5. Discussion

5.1. Summary and discussion of results

In this mixed methods case study, the implementation of an SHT, installed in 137 apartments in two multi-apartment buildings, was monitored for three years using survey, observational, interview and measurement data. Over the three years, annual savings below 10 % could be realised. The analysis shows that for a highly insulated building – a material setting that should generally be quite favourable for the application of demand-side management – the expectation that SHT will typically achieve 20–30 % savings could be exaggerated. This study argues that the main reason could be interaction problems between technological affordances and occupants' comfort practices: From SHT leading to a homogenisation of the indoor thermal conditions and comfort practices that seek and result in varying patterns.

Research suggests that SHTs, such as the one analysed in this paper, achieve their full efficiency potential through multi-zone control [110] and by shifting heat loads, reducing flow temperatures and limiting peak loads [4,13]. Such demand-side management also offers further potential by increasing the flexibility and overall efficiency of the energy grid by facilitating the integration of renewable energy, e.g., through the electrification of the heating supply or low-temperature district heat [4,63].

This study supports previous findings that these system characteristics have consequences for occupants: Due to the built-in inertia, the system behaviour requires more homogeneous indoor temperatures and makes the system less flexible for occupants [61,66]. Because it responds more slowly to adjustments in the heating control, it is no longer possible to have fast feedback when adjusting the heating [13]. Thus, homogeneous temperatures and efficiency are mutually supportive. Furthermore, the system should align well with strong building insulation, which reduces heat loss and increases the inertia and homogeneity of indoor temperatures even further [107].

However, for a long time, occupants in Germany have mainly experienced the typical material setting of buildings with high energy demand (low insulation) and conventional heating systems (primarily gas and oil). In this setting, typical comfort practices have evolved: Occupants have become used to variations in indoor conditions and have learnt to regard them as a preferred state.

The analysis of the comfort practices of 265 households in conventional multi-apartment buildings lends further support to the prevalence of heterogeneity of temperature patterns within homes. And similar patterns can be found not only in Germany [67,68,81]. Different studies have provided insights into the many mechanisms that can lead to variations, not only in comfort practices but also in the ensuing temperature patterns within smart homes: From conflict within households [70] and caring practices [67] to the engagement of individuals with the building technologies itself [12].

Even though it is often argued that occupants waste much energy in old buildings, the prevalence of prebound effects [20,111] shows that, on average, occupants behave quite economically in these settings. Furthermore, if building technologies are upgraded, these practices will not automatically adjust to the material affordances, i.e. occupants will not necessarily behave as designers of demand-side management intend them to. It is, therefore, unclear how much savings can realistically be expected, and savings of 7 % do not seem so bad in this context, even though they are likely not economical.

By comparing old with new buildings and how comfort practices evolve with different material settings, this study also provides insights into the shifts from prebound effects to EPGs with increasing energy efficiency in building technologies [111]. In accordance with research on mental models of thermostat use [95,97,102] and on comfort practices in old buildings [112], this study implies that heating practices in many old buildings might not be as bad as often described by advocates of SHT. Galvin [112] argued that only a small proportion of households are responsible for the largest share of heating energy consumption and whose behaviour should, therefore, receive priority attention by energy policy. Although this statement has to be qualified somewhat in the light of interaction effects between dwellings, e.g. free-rider effects due to internal heat transfers [107,109,113], there could be a similar pattern in new buildings with smart heating controls. There will be many households whose practices will, after some time, align well with the technologies in place [12,72] due to the co-evolution between practices and material arrangements.

When SHT favours homogenisation, the temperature level at which this homogenisation occurs matters. There remains uncertainty as to what extent SHT can counteract the trend towards higher indoor temperatures in evenly heated homes. Previous research suggests that, in modern, well-insulated and centrally-heated buildings, average temperatures and, thus, energy consumption increases [114]. Research also shows that people become accustomed to these higher temperatures in the long term [53]. The inertia of SHT and the difficulties of adjusting temperature upwards for short times could support this trend: Occupants can become used to permanently heat at a higher level and open windows when seeking variation. Alternatively, SHT could offer the option of heating rooms only to a basic level, in which case occupants would have to make greater use of other adaptation options, such as keeping their bodies warm rather than whole spaces [66,115–117]. The results of this study indicate that – compared to a modern but conventionally heated building – SHT leads to average savings despite high consumption.

Future developments of heating energy consumption in buildings thus depend on how comfort and the use of these technologies will be negotiated. Intermediaries such as building managers could support residents in finding a compromise between comfort and energy savings [11], e.g. by providing alternative means for achieving comfort [116,118]. Conversely, escalating expectations and co-evolving technologies could also pressure technology developers to prioritise comfort over savings, intensifying rebound effects.

5.2. Limitations

This study concentrated on what people do to achieve comfortable indoor conditions, how they interact with their building technologies, and how this affects heating energy consumption.

By focusing on doings, one limitation of the study is the reliance on self-reported behaviour when analysing habituated and routinised activities. This problem is addressed by triangulating data and methods. All in-depth cases have been chosen based on cross-validated evidence from survey, qualitative, and measurement data. Still, there remains ambiguity and interpretative flexibility, particularly for the measurement and survey data, regarding the detailed understanding of what happened in the households [119]. Likewise, uncertainty remains about why residents behave in specific ways. However, while many studies rely more on qualitative data to explain how different elements shape comfort practices, this study focuses more on the outcomes of comfort practices regarding behavioural patterns. Thus, while practices can be shaped by various ideas of comfort or other elements, the ensuing patterns are the focus here.

A major challenge, but also a strength, of this study is the nature of the varied data. The qualitative data - such as observations made during home visits with artisans or field notes collected while assisting residents with heating problems - is very diverse. The standardised survey, however, covers many aspects in detail but leaves many gaps regarding contextual knowledge, e.g., when figuring out why occupants tilt windows for long periods. Meaningful multivariate statistical analysis is impossible because of the amount of relevant and interacting variables and the small sample size. The sample size is due to the limited number of households in the case study buildings and the non-response rate. Response rates are restricted, among other things, by the length and detail of the questionnaire, which is particularly challenging for occupants with limited language skills. However, there are no signs of systematic bias among respondents.

Caution must also be paid to the long-term implications of how practices will evolve with the SHT. The study can only provide a first snapshot of the interactions with SHT. As practices are relatively stable but also constantly changing, more research is needed on how practices will evolve in relation to SHT in the long term. It is conceivable that practices will change if households attribute more relevance to heating energy consumption. In particular, steadily rising energy prices over long periods and more regular feedback – now mandatory in Germany in the form of monthly information on heating energy consumption – could help change comfort practices.

While energy prices have risen sharply in 2022/23 due to the Russian invasion of Ukraine and the ensuing energy crisis around Europe, this only temporarily affected household energy consumption patterns. In the heating season 2022/23, households across Germany significantly reduced their indoor temperatures and heating consumption [91], and this effect is also evident in the case study and reference buildings. The differences between the smart and reference buildings with conventional TRVs stayed constant, confirming the overall savings effect from the SHT. The principal analysis in this paper is not affected by this effect, using data from before the energy crisis. Since the general reduction of energy consumption should not affect the relationship between temperature patterns and heating energy consumption levels, the regression results should also not be affected. This was also confirmed when looking at the regression analysis for the previous year (not shown).

Lastly, it is essential to mention that the heating patterns described here do not cover the entire spectrum of patterns apparent in the field. Instead, they represent extreme cases, and many households will fall between them. Furthermore, while this is a German case study, the discussion of the relevant literature on SHT [3,4,13,15,72] and patterns of indoor conditions in households [67,68,81,82,120] shows that the issues discussed are not specific to the German context. Certain aspects, such as the commonality of tilting windows [79,121] or the relevance of tenancy in multi-apartment buildings, are more specific to the German context. However, the main issue of SHT favouring homogeneity and comfort practices contributing to variation in indoor conditions seems to be a general one.

5.3. Policy implications

This study indicates that technical estimates of savings from SHT are based on assumptions of standardised and homogeneous user practices. These estimates do not sufficiently consider these practices' varied and diverse nature, which has evolved from specific spatial and temporal contexts. I suggest that a more realistic and robust assessment could, on the one hand, reduce mistrust on the part of potential customers (expectation management), such as housing companies. On the other hand, it could trigger a discussion about necessary accompanying measures. It could shift the focus from technical to social solutions, as it becomes clear that sustainability is not a purely technical task [122] but involves the redefinition of social practices [123].

Currently, interest in changing practices seems low. Instead, many stakeholders point out that technical solutions are not yet sufficiently mature and more technical development is needed: Occupants are trapped in existing mental models and habits. They often have little interest in learning how to use new technologies most efficiently. And many also think these technologies have little benefits and still suffer from many problems [73]. Landlords, however, are happy to continue to rely on established and robust technology that causes few problems for tenants. Manufacturers, again, are interested in selling SHT, but – innovating in the particularly intransparent market of building energy consumption – they often stick to their competitors' established marketing strategies, promising savings up to 30 % [4,9] and hope that the regulatory wind will shift in their favour. They also prefer to point to the technology's functionality and users' misbehaviour rather than dealing with the question of how they can adapt the technology to the contexts in which it is used. Consequently, the diffusion of these technologies remains low, and energy performance gaps prevail.

More generally, this includes a call for policymakers and technology developers: They should not aim for optimal solutions that only work under unlikely boundary conditions. Instead, they should search for robust technologies and how they can be aligned with other approaches to achieve the desired goals. There are some initial approaches in this direction, i.e., in architecture [124].

My research implies that SHT could play an essential role in the sustainability transformation of buildings, particularly in well-insulated buildings or those with high thermal mass, and when occupants seek a homogeneous but relatively low (at the lower end of the comfort scale) indoor climate. However, this would require shifting practices: From keeping spaces at high temperatures to alternative ways of achieving comfort [116]. Here, personalised adaptation options should receive greater attention, from warmer clothing to heating systems directed at the body instead of the room [115]. The success of SHT thus depends on being embedded and coupled with other technical and non-technical elements instead of reproducing energy-intensive ways of providing comfort [76].

Uncertainty remains about how SHT would work in older buildings with higher energy demand. A strategy where system feedback is significantly reduced seems to make less sense in buildings where occupants rely on fast feedback to heat rooms for shorter periods without keeping the whole building mass at high temperatures. Load shifting could still work depending on the thermal mass of the building, particularly for residents who are at home most of the time. However, this would only make sense if energy is much cheaper in times of high supply. Occupancy detection – supporting occupants to lower temperatures during absence and turning heaters down in unoccupied rooms – could be promising for occupants who are little concerned with saving energy. As occupants often are not aware of what is best in which context, they could be supported on how to negotiate comfort and efficiency in practice. Intermediaries at the interface between technology and users can support these negotiations, thereby mediating between material and practical affordances [11]. In particular, building managers or – as has happened in this case study – support staff who understand occupants and technology are essential mediators. They should receive greater attention in energy policy.

Again, the research conducted here implies that focusing on one-size-fits-all solutions, technical potential, and technical innovation is too narrow. What matters is the interplay between technology and practices. Context-sensitive approaches are needed to bridge the gap between building vs. behaviour approaches.

CRediT authorship contribution statement

Simon Moeller: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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