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Impact of the energy crisis on indoor temperatures and thermal comfort in UK houses during winter 2023

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ABSTRACT

Geopolitical, health and economic events have led to an accumulated surge in energy prices in the UK at the beginning of the 2020s. In response, studies and media reports show that households have had to reduce the running of their heating systems to cut their energy bills. However, there is limited research on the impact of this context on indoor thermal conditions and occupants' ability to meet their thermal comfort needs. This study aimed to address this research gap. It employed the mixed-method research methodology and used nine homes in Plymouth as case studies. Undertaken research work involved monitoring indoor air temperatures for two months, January and February 2023. In parallel, a thermal comfort survey and interviews were undertaken with the residents of the examined cases. Results show that six of the nine examined households were unable to run their heating systems to warm their homes. In four cases, the average hourly air temperatures ranged between 11 and 16 °C, which is below the British Standard's recommended temperature of 18 °C for comfortable and healthy domestic spaces. Some participants decreased their energy consumption by 27 % compared to the previous year, utilising behavioural measures to compensate for reduced heating usage and maintain a level of thermal comfort. Affected by their indoor environments, participants reported different comfort thresholds with average comfortable air temperature ranging between 12 and 20 °C. The findings of this research demonstrate the impact of energy prices on occupants' energy usage and their ability to manage cold environments while preserving their thermal comfort.

1. Introduction

The war in Ukraine has triggered a global energy crisis, and European countries have experienced a surge in energy prices [1,2]. On the first day of the war, the 24th of February 2022, the wholesale prices of gas and electricity increased in the continent by 115 %, and a further increase of 137 % was recorded by the end of July 2022 [3]. This escalation in energy prices came on top of a pre-existing upward trend in the summer of 2021 triggered by the post-COVID-19 pandemic recovery [4,5]. The increase in energy prices has significantly affected inflation rates in the EU leading to substantial increases in living costs [6]. Focusing on the UK, the inflation rate reached its highest level in 41 years, peaking at 11.1 % in October 2022, before it slowly started to decrease, but it was still at 6.7 % in August 2023 [7]. To face these high inflation rates, households in the country had to cut their expenses. It has been reported that, in November 2022, 63 % of households in the country had to reduce their energy consumption due to financial constraints. This was nearly double the number of households that had to take similar actions in December 2021 [8–10].

In response, the UK Government has adopted a range of financial measures aimed at helping households pay their bills and keep their homes warm in winter, including introducing the Energy Price Guarantee (EPG) scheme in October 2022. The aim of this new scheme was to limit the typical annual bills for users to no more than £2500. Also, households received a £400 Energy Bills Support Scheme in instalments between October 2022 and March 2023. However, energy bills for winter 2022–2023 were still at the highest levels on record [7,11]. In 2022, 13.4 % of households were estimated to be in fuel poverty, increasing from 13.1 % in 2021. Affordability-wise, the number of households that had to spend more than 10 % of their incomes on

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domestic energy was estimated at 36 % in 2023, increasing from 10 % in 2021 [12]. The high energy bills and living costs have led many households to face the so-called 'heat or eat' dilemma [66]. The consequences were dire. According to a report published by the House of Commons in 2023, ''*there were 4706 excess winter deaths caused by living in a cold, damp home in England, Scotland, and Wales*''. The longer-term impact of reduced health is still to emerge.

Studies evidence that cold homes have negative impacts on occupants' health and wellbeing. Building occupants experiencing cold conditions are subject to increased risks of illness, including respiratory and cardiovascular illnesses. In addition, studies have found that cold homes may cause mental health problems, such as negative feelings, stress, and isolation [13–15]. According to BS EN 16798-1-2019, the minimum temperature recommended for the heating season in domestic spaces is 18 °C [16]. This 18 °C minimum threshold is also recommended by research studies, the World Health Organization and the UK Health and Security Agency [14,17,18]. Table 1 shows the recorded average air temperatures in the UK between 1978 and 2010 as reported by literature and studies. Data indicates that average temperatures in houses ranged during this period between 17.5 °C and 21.6 °C, which are highly close to, or above, the minimum recommended threshold by standards. Studies suggest that, generally, indoor air temperatures have been increasing over the years. Occupants of residential buildings have experienced a substantial enhancement in thermal comfort due to the installation of central heating systems, which commenced in the 1970s [19].

However, there has been no data about thermal conditions in residential buildings in the country for the years after 2020, which is the period that witnessed the recent surge in energy prices. Hence, whilst it is evident that households have reduced their energy consumption in homes [11,20,21], the thermal conditions they have experienced and their abilities to maintain their thermal comfort are unknown. This study aims to address this research gap. The results of this study provide new data about indoor thermal conditions in residential buildings in the UK under duress. Also, they provide new insights into the impact of increasing energy prices on building occupants' energy consumption and their capabilities to maintain their thermal comfort during winter. Results could help scholars, designers, and policymakers to better understand building occupants' reactions towards increasing energy prices in cold conditions and their thermal adaptation capabilities.

Table 1
Previous literature determining indoor thermal conditions in living rooms in winter in the UK.

Reference	Study year	Sample size		Average air temperature (°C)
Mavrogianni et al. [19] – UK Nation Field Survey of House Temperatures *	1978	901 houses		Daily 18.3
Hunt and Gidman [48]	1978	Large scale survey in all housing types		Daily: 18.3
Nevrala and Pimbert [67]	1977–78	33 Houses	Uninsulated houses	Daily: 19.8
			Insulated houses	Daily: 20.3
			New houses	Daily: 21.6
Vadodaria et al. [38] – EHCS*	1986	2177 houses		Daily: 18.0
Vadodaria et al. [38]	1994	515 houses		Daily: 19.3
Vadodaria et al. [38] – EHCS*	1991	25,000 houses		Daily: 18.6
	1996	—		Daily: 18.1
Oreszczyn et al. [68]	2001–02 2002–03	1604 houses of low-income households		Median standardized 19.1
Summerfield et al. [69]	2005	15 houses		Daily 19.3
Yohanis and Mondol [70]	2004–05	15 houses		Daily 17.5
Vadodaria et al. [38]	2010	20 houses		Daily 17.8 Evening 18.7

* Data from the English House Condition Surveys (EHCS) and the UK National Field Survey of House Temperatures, as presented in previous literature, were referenced. Direct access to these datasets was not available for this study.

2. Aim and objectives

This study aims to investigate the influence of the increases in energy prices on thermal conditions in residential buildings during winter 2023 and the capabilities of building occupants to maintain their thermal comfort. To achieve this aim, the research had to address two objectives:

- Objective 1: Determine indoor thermal conditions in residential buildings and compare them with the 18 °C recommended minimum threshold of the BS EN 16798-1:2019 standard and pre-energy crisis thermal conditions in homes.
- Objective 2: determine the level of thermal comfort households were able to achieve during winter 2023 whilst facing the surge in energy prices.

3. Research methodology

This study adopted the mixed-methods research methodology in which quantitative and qualitative data are collected and analysed (Fig. 1). The utilisation of quantitative and qualitative research methods in research studies has been found to help increase research credibility and deepen understanding of the subject matter [22,23]. The research used nine residential buildings in Plymouth, Devon, as case studies. This county is a part of the UK's South West region, which has a relatively warm climate representing a "best case scenario" when compared to other regions in the country [24,25]. On average, between 1991 and 2020, the South West England region was 0.8 °C–1.8 °C warmer in January than the rest of the country (Fig. 2). Conducted research work involved monitoring air temperatures in houses, undertaking a thermal comfort survey, and conducting interviews. The monitoring of indoor air temperatures and the survey were undertaken for two winter months, January and February 2023. These two months were considered to represent typical winter conditions in the UK [26]. The interviews were undertaken during May 2023.

3.1. Case studies

This research used nine houses in and around the city of Plymouth as case studies (Table 2). Due to the limitations of time and resources, it was not possible for the research team to examine houses and communicate with residents of other regions in the UK. However, to conclude with comprehensive results and understanding, through the purposive sampling technique, the recruitment of participants was done by considering four criteria. The first criterion was that households have been living in their dwellings for at least three years so that a comparison could be made between the examined winter period in this study and pre-energy-crisis periods. The second criterion was related to having participants of different demographics so that a range of different scenarios could be explored. The study included households of diverse sizes, encompassing occupants of both genders and various age groups. The third criterion was about participants having an overall stable income over the past three years so that the impact of increasing energy prices on energy consumption could be better investigated. Whilst it was not possible to ask participants about their income, they were asked about their employment status to ensure that no major changes in jobs, their main income streams, have occurred during the past three years. With the fourth criterion, the study considered examining buildings of different patterns and insulation features. Although examining the impact of these factors on indoor conditions is outside the scope of this

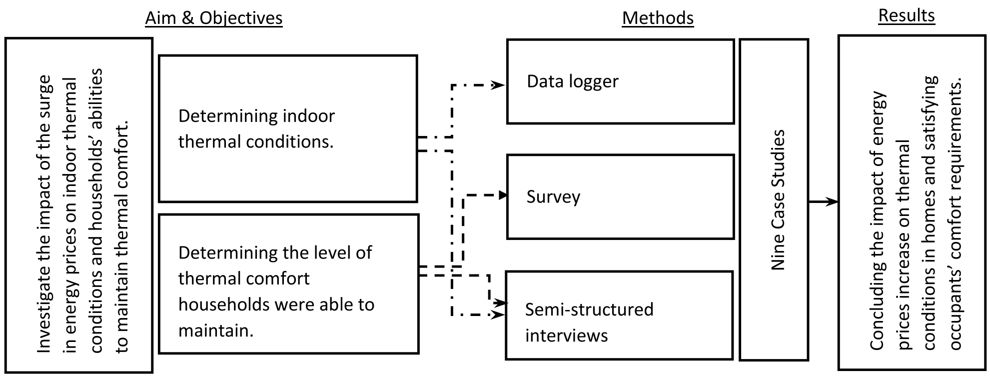


Fig. 1. Research methodology.

	Zone A: Belfast	Zone B: Edinburgh	Zone C: Plymouth	Zone D: London
Jan	8.2	7.2	9.0	7.4
Feb	8.7	7.9	9.2	8.0
Mar	10.4	9.7	10.9	10.9
Apr	12.8	12.1	13.2	14.1
May	15.7	14.9	15.9	17.3
Jun	18.1	17.4	18.4	20.2
Jul	19.7	19.2	20.2	22.7
Aug	19.4	19.0	20.3	22.2
Sep	17.3	16.8	18.4	19.1
Oct	13.8	13.3	15.1	14.8
Nov	10.6	9.8	11.9	10.6
Dec	8.4	7.3	9.6	7.8

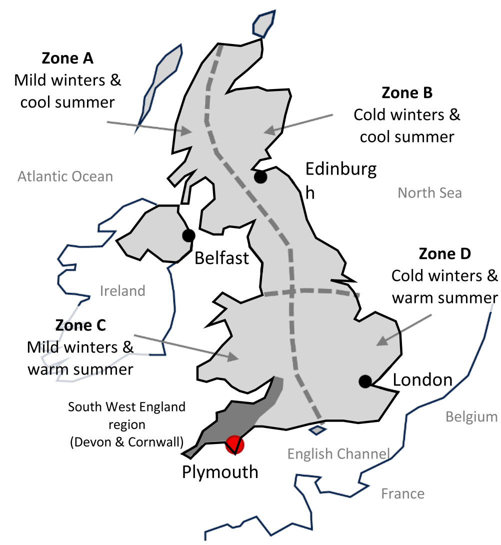


Fig. 2. Average temperature in the four climatic regions of the UK (1991–2020) – Left. UK map showing the location of Plymouth and the climatic zones of the country – Right.

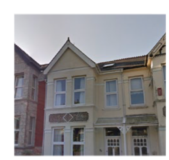
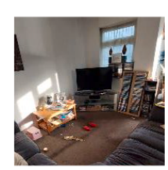
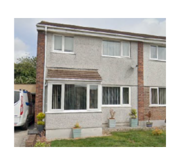
study, this criterion was considered to allow the examination of varied buildings to increase results representativeness and reliability. Ethical approval for this study was obtained in line with the procedures of the lead author's institution.

3.2. Indoor thermal conditions

The thermal sensation of building occupants is affected by a wide range of interrelated quantitative and qualitative factors. Among these, there are four microclimatic factors, which are air temperature, relative humidity, mean radiant temperature (MRT) and air velocity [27,28]. This study focused on monitoring air temperature in its investigation of the impact of the increases in energy prices on indoor thermal conditions. Air temperature is the most effective factor on occupants' thermal sensation in the context of this study [29,30]. Also, all the explored previous studies measured air temperature when examining indoor thermal conditions in homes (Table 1). The humidity level is not as sensible by occupants as temperature because there are no humidity sensors in the human body. Its impact is particularly noticeable in hot-climate regions where high humidity levels prevent the body's cooling mechanism of sweat evaporation, which is not applied to this study [29]. With regard to air velocity, without mechanical airflow, studies assume still air in buildings with air velocity below 0.1 m/s, which has minimal impact on thermal sensation. For the cold conditions of winter, none of the examined cases in this study included mechanical air flow [31,32]. MRT is the most complicated factor to be measured, and it is related to the temperature of the surfaces surrounding the human body [29,30]. In indoor spaces, in cold-climate regions, studies have shown that MRT highly matches air temperature, and it is unlikely to have practical benefits from measuring it [33,34].

Nine Hobo dataloggers were used to monitor and record indoor air temperatures in the examined case studies. Hobo datalogger's temperature measurement range is −20 °C to +70 °C, and its accuracy is ±0.21 °C. They have been widely used in previous studies aiming to monitor and record indoor thermal conditions [35–37]. To verify the readings of the specific dataloggers used in this study, they were calibrated by a senior technician, and they were tested for two days before being delivered to the participants. They were set to record hourly indoor air temperature in a residential space. The testing ensured that the air temperature measurements of the nine dataloggers were matching and as per their specified measurement ranges and accuracy levels. Following that, the Hobo dataloggers were fitted in the living rooms of the examined nine residential buildings. Living rooms are the spaces where building occupants spend major parts of their time undertaking a variety of activities. The majority of previous studies recording indoor thermal conditions in residential buildings have focused on living rooms [38]. Dataloggers were positioned in places where average air temperatures are measured; they were placed away from heat or cold sources,

Table 2
Examined cases in this study.

Cases	Occupants	House			
		Pattern and size	Approximate age	Insulation status	Photo
Case 01	Three-member household	Three-bedroom semi-detached house	60 years	Insulated	
Case 02	Three-member household	Two-bedroom terrace house	70 years	Uninsulated	
Case 03	One-member household	Two-bedroom semi-detached house	70 years	Partially insulated (roof insulation only)	
Case 04	Six-member household	Three-bedroom terrace house	70 years	Uninsulated	
Case 05	Five-member household	Three-bedroom ground floor flat	60 years	Uninsulated	
Case 06	Two-member household	Two-bedroom semi-detached house	70 years	Fully insulated	
Case 07	Four-member household	Three-bedroom terrace house	120 years	Partially insulated (roof insulation only)	
Case 08	Three-member household	Two-bedroom middle-floor flat	70 years	Fully insulated	
Case 09	Two-member household	Three-bedroom semi-detached house	70 years	Fully insulated	

such as heaters, windows, and direct solar radiation (Fig. 3).

3.3. Interviews

Interviews with residents of the examined cases were undertaken to supplement collected data from the other sources; they allowed to obtain detailed information about the impact of the increases in energy prices on indoor thermal conditions as experienced by occupants, and their used approaches to achieve thermal comfort. These were 10–15 min semi-structured interviews. This format of the interviews allowed the research to have systematic and uniform data collection from all participants as well as giving a space to expand on different topics that could be raised by the participants [39,40]. One interview was undertaken with a participant from each case study following completing the

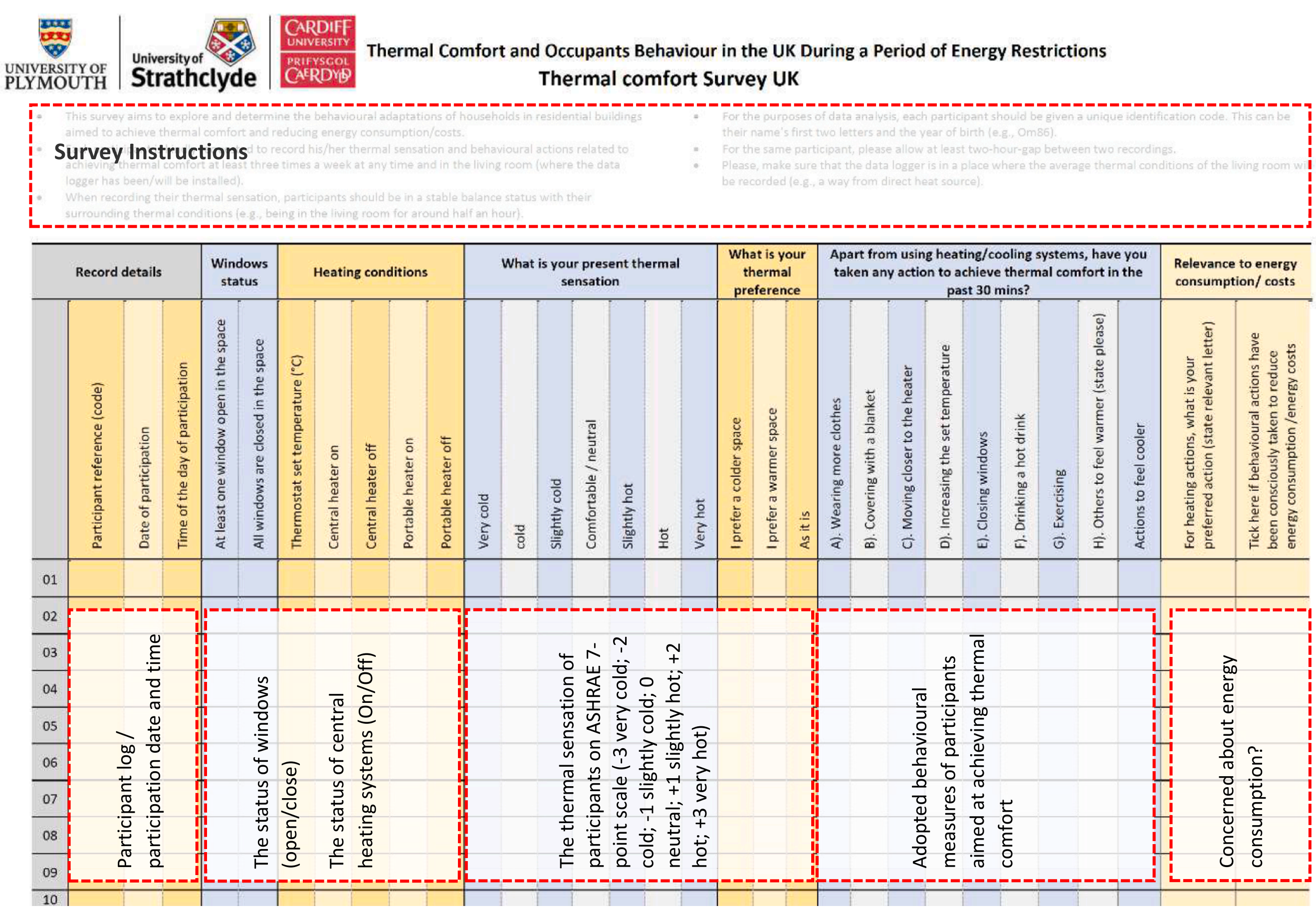
Fig. 3. Three examples showing the positioning of the dataloggers in the examined cases.

survey. They were conducted in-person and virtually via Zoom. With regard to the general structure, interviews included questions about the way participants heated their homes and whether there were any differences in comparison to previous years; participants' overall thermal sensations; adopted measures to achieve thermal comfort; energy bills; and whether reducing energy consumption was a concern.

3.4. Thermal comfort survey

A thermal comfort survey was undertaken to determine the thermal sensations of participants and their usage of heating systems. Participants were given a diary sheet to complete, identifying participation date and time, recording thermal sensations using the ASHRAE 7-point scale of −3 to +3, and indicating the operational status of the heating system (Fig. 4). Participants were also asked to identify any adaptation measures they used aiming at achieving thermal comfort whilst reducing their energy consumption. Thermal comfort studies have shown that building occupants are not passive respondents regarding achieving thermal comfort [41,42]. In cold conditions, they tend to adopt a range of behavioural measures to maintain their thermal comfort. Based on previous literature, six adaptive measures were included in the survey: increasing clothing layers, using a blanket, having a hot drink, moving closer to a heater, closing windows, and practising exercises [43–45].

The survey sheet included instructions on how to complete the survey, which were also verbally communicated to participants at the beginning of the study. Participants were asked to record their thermal votes and adaptive behaviours at least once a week while undertaking their normal domestic activities in their living rooms. To collect true thermal votes, participants were asked not to record their thermal votes unless they were in a stable and settled state within their environments. More specifically, they were asked to record their thermal votes after



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Thermal Comfort and Occupants Behaviour in the UK During a Period of Energy Restrictions

Thermal comfort Survey UK

Survey Instructions

- This survey aims to explore and determine the behavioural adaptations of households in residential buildings aimed to achieve thermal comfort and reducing energy consumption/costs.
- [illegible] to record his/her thermal sensation and behavioural actions related to achieving thermal comfort at least three times a week at any time and in the living room (where the data logger has been/will be installed).
- When recording their thermal sensation, participants should be in a stable balance status with their surrounding thermal conditions (e.g., being in the living room for around half an hour).
- For the purposes of data analysis, each participant should be given a unique identification code. This can be their name's first two letters and the year of birth (e.g., Om86).
- For the same participant, please allow at least two-hour-gap between two recordings.
- Please, make sure that the data logger is in a place where the average thermal conditions of the living room wil[l] be recorded (e.g., a way from direct heat source).

	Record details			Windows status		Heating conditions					What is your present thermal sensation							What is your thermal preference			Apart from using heating/cooling systems, have you taken any action to achieve thermal comfort in the past 30 mins?									Relevance to energy consumption/ costs	
	Participant reference (code)	Date of participation	Time of the day of participation	At least one window open in the space	All windows are closed in the space	Thermostat set temperature (°C)	Central heater on	Central heater off	Portable heater on	Portable heater off	Very cold	cold	Slightly cold	Comfortable / neutral	Slightly hot	Hot	Very hot	I prefer a colder space	I prefer a warmer space	As it is	A). Wearing more clothes	B). Covering with a blanket	C). Moving closer to the heater	D). Increasing the set temperature	E). Closing windows	F). Drinking a hot drink	G). Exercising	H). Others to feel warmer (state please)	Actions to feel cooler	For heating actions, what is your preferred action (state relevant letter)	Tick here if behavioural actions have been consciously taken to reduce energy consumption /energy costs
01																															
02																															
03																															
04																															
05																															
06																															
07																															
08																															
09																															
10																															

Participant log / participation date and time

The status of windows (open/close)

The status of central heating systems (On/Off)

The thermal sensation of participants on ASHRAE 7-point scale (-3 very cold; -2 cold; -1 slightly cold; 0 neutral; +1 slightly hot; +2 hot; +3 very hot)

Adopted behavioural measures of participants aimed at achieving thermal comfort

Concerned about energy consumption?

Fig. 4. Survey form.

being in the living rooms for at least 30 min. They were instructed not to fill-in the survey if they had just arrived from outside. Participants were asked to assign themselves unique codes to facilitate data analysis for multiple participants from the same house.

3.5. Data analysis

Using data collected from the fitted dataloggers in the examined cases, this study determined the percentage of recorded instances when air temperatures were below 18 °C, which is the minimum threshold for living rooms as determined by BS EN 16798-1-2019. This percentage was determined for one specific time of the day, which is at the hour 18:00. This hour was selected to determine the general thermal conditions experienced by occupants as this is the period when living rooms are mostly occupied [38,46]. Also, average daily air temperatures were determined for the whole day period and compared with the 17.5–21.6 °C average indoor temperature range as determined by studies in houses for pre-energy crisis periods (Table 1). Low air temperatures, even if they are out of the occupation period, could have negative impacts on residents especially if they are associated with high humidity levels as they could lead to condensation and mould growth [47–49]. This analysis allowed the study to examine the compliance of indoor thermal conditions in residential buildings with the minimum recommended temperature threshold and make a comparison with thermal conditions households used to experience before the energy crisis.

By correlating the thermal comfort survey data with datalogger data, this study determined the thermal comfort requirements of participants, and the levels of thermal comfort they were able to achieve during winter 2023. Data analysis included determining the percentages of cold and comfort votes, and the comfort air temperature ranges (Table 3). Within the ASHRAE 7-point scale, thermal votes from −1 to +1 were used to define the comfort zone. The comfort temperature range was determined by the temperatures associated with participants' thermal comfort zone. The average comfort temperature is calculated as the mean of the temperatures associated with the comfort zone. The neutral temperature, defined as the temperature at which at least 80 % of individuals feel thermally comfortable (thermal sensation score of 0), was determined through a regression analysis that examined the relationship between the Mean Thermal Sensation Vote and the recorded indoor air temperatures [44,50]. The analysis also included determining the instances when participants satisfied their thermal comfort requirements by running the heating systems and using adaptive measures. This analysis allowed the research to highlight the approaches used by participants to maintain their thermal comfort. The percentages of instances associated with running the heating systems and using adaptive measures were determined for each participating household. The most used behavioural actions by participants to achieve thermal comfort were identified.

Using the IBM SPSS 23 statistical package, Pearson correlation analysis was undertaken to determine the statistical correlations between the examined variables, including the correlation between indoor thermal conditions, participants' thermal comfort levels, and the utilisation of adaptive thermal comfort measures. This analysis allowed to further understand found results as well as evidencing the rigorousness and reliability of the research findings. Undertaken interviews were transcribed and colour-coded. Interview data was used to explain collected quantitative data and to develop a deeper understanding of the impact of energy prices on indoor conditions and occupants' comfort.

Table 3
Example showing the calculation of the average comfort temperature and the comfort temperature range.

ASHRAE Scale		Survey data	Datalogger data	Drawn conclusions
Hot Zone	Very hot	+3	23	Comfort temperature range: 19°–21 °C
	Hot	+2	22	Average comfort temperature: 20 °C
Comfort Zone	Slightly hot	+1	21	Percentage of comfort votes: 3/7 = 42 %
	Comfortable	0	20	Note: survey and datalogger data are assumed values for this example.
	Slightly cold	−1	19	
Cold Zone	Cold	−2	18	
	Very cold	−3	17	

3.6. Bias and validity

Measures were taken to minimise the risks of social desirability bias (SDB) and common methods bias (CMB), which could negatively affect the validity and reliability of studies. The former is associated with surveys and interviews, and it occurs when participants provide responses that are believed to be socially favoured, not their true ones [51,52]. The latter occurs when one research method is used to examine a range of variables [53].

Three measures were considered in this study to minimise the risks of CMB. The main measure, as shown in Fig. 1, was to use three research methods so that each variable is examined using at least two methods. Secondly, the study considered what is called in literature Temporal Separation. Data were collected from participants at different points in time. The survey responses were collected over two months, and the interviews were undertaken around two months after the survey. Thirdly, the survey and interview questions were clear, simple, and concise. There were no complicated and unclear questions that could not be understood by participants leading to inaccurate answers [54,55]. For the SDB, the use of the mixed-methods methodology was essential to minimise the risks of this kind of bias. Self-reported data in the survey and the interviews was triangulated with objective data recorded by the dataloggers. In addition, following literature recommendations, there were no guided questions, participants' anonymity was ensured, and no preferred or standardised practices with regard to energy consumption and thermal comfort were defined for participants [56,57].

4. Results and analysis

4.1. Results overview

Hourly indoor air temperatures in the living rooms of the nine examined cases were recorded for two months between the 1st of January – the 28th of February 2023. In parallel, occupants of the examined cases participated in the thermal comfort survey conducted as a part of this study. The recording of indoor air temperatures and the survey started in cases 02 and 06, respectively, on the 19th and the 20th of January. Although this affected the length of the undertaken monitoring and the number of collected votes, it had no impact on the validity and reliability of the results. In total, 10,416 temperature recordings were collected. Eight Interviews were conducted during May 2023 with occupants of the examined houses. Tenants of Case 02 did not participate in the interviews. The total length of recorded interviews was around 85 min. Four of the interviewees provided energy consumption readings during the interviews.

Thirteen of the building occupants participated in the thermal comfort survey, and 210 thermal comfort votes were collected. Six of the participating households confirmed in the survey and the interviews that they were concerned about their energy consumption and that they reduced running their heating systems. The other three households reported that they did not aim to reduce their energy consumption (Table 4). Each case included one participant, except cases 05 and 09. In these two cases, the responses of each participant were separately analysed, including recorded thermal sensations and used adaptive behaviours. This allowed the research to better achieve its aim of examining people's experiences and their adaption approaches to cope with the

Table 4
Number of survey participants and collected thermal comfort votes.

Case	Number of participants	Gender	Age (years)	Number of votes	Aimed to reduce energy consumption	Case	Number of participants	Gender	Age (years)	Number of votes	Aimed to reduce energy consumption
01	1	Female	35	19	Yes	06[c]	1	Male	34	6	No
02[a]	1	Male	38	9	Yes	07	1	Male	50	20	Yes
03	1	Male	37	19	Yes	08	1	Male	48	59	No
04	1	Male	41	16	Yes	09	2	1 Male, 1 Female	62, 66	26	No
05[b]	4	2 Males, 2 Females	63, 20, 54, 24	36	Yes	Total	13	9 Males, 4 Females	25–66	210	

a. Case 02: participants joined the study on the 19th of January 2023.
Participants did not participate in the interviews.
b. Case 05: data could not be retrieved from the datalogger for technical issues.
c. Case 06: participants joined the study on the 20th of January 2023.

cold conditions and manage the high energy prices.

4.2. Recorded indoor air temperatures

Dataloggers data shows that the examined cases vary in their indoor thermal conditions (Table 5; Figs. 5 and 6). The average daily air temperatures in the living rooms of cases 2, 3, 4 and 7 ranged between 11 and 16 °C. On an hourly basis, temperatures in the living rooms of these cases were found below 18 °C for more than 95 % of the recorded instances during January and February 2023. At 18:00, which is when the living rooms are mostly occupied, temperatures were below the recommended thresholds of 18 °C for over 70 % of the recorded instances, and their averages ranged between 12 and 17 °C. Cases 1, 6, 8 and 9 offered occupants warmer thermal conditions. At 18:00, occupants enjoyed temperatures above 18 °C for over 75 % of the recorded instances. The average temperature at 18:00 in these cases ranged between 19 and 21 °C. The average hourly air temperature in these cases for January-February 2023 ranged between 18 and 20 °C.

4.3. Indoor thermal conditions & energy prices

The variation in the air temperature between the examined cases can be traced back to a range of reasons, including factors related to occupants, dwelling design and structure, and the heating systems [26,58]. However, whilst these factors could also have an impact, the results of this study indicate a direct correlation between the thermal conditions of the examined spaces and occupants' tendencies to reduce their energy consumption (Fig. 7).

The participants of cases 6, 8 and 9 stated that they did not aim to reduce their energy consumption and they prioritised their health and thermal comfort over making energy savings. This attitude justifies the relatively high air temperatures in these cases in comparison to the other examined cases. In the interview, participant 06 described and justified the way they run their heating system saying '*we have during the winter the radiators running all the time, the set temperature is around 25 °C. My wife likes to be warm, so we keep the heating on because of that*'. A similar reason was given by the participant of case 09. However, Case 08 presents a different reason, which is that the participants enjoyed a fixed tariff from before the energy crisis, and, hence, they were not affected by the surge in prices. Acknowledging the impact of the energy prices if they had not enjoyed the fixed tariff, the participant of Case 08 stated '*if we were to be affected by the energy price, we probably had to go through the routes of putting on jumpers or blankets, but we are lucky*'.

The participants of cases 01, 02, 03, 04, 05 and 07 stated in the survey and the interviews that, starting from February 2022, they reduced running their heating systems and/or the setpoint temperatures to reduce their energy bills. The participant of case 04 described the way they run the heating system saying '*if the weather is not very very cold we tried to avoid switching the heater on most of the time. We try to use thick clothes and blankets*'. When asked about what air temperature they considered cold and run the heating system, the response was that when the temperature is below '*12* and *13 °C*'. The participants of Case 03 reduced their energy consumption by dropping the setpoint temperature from 18 °C to 15 °C and reducing the number of hours the heating system is running. Similar approaches were reported by the participants of cases 04 and 07. Except for case 01, it can be seen that the average temperatures at the hour 18:00 in these cases were lower than in cases 06, 08 and 09 (Fig. 6; Table 5). The participant of case 01 stated that they neither lowered the setpoint temperature nor reduced running the heating system in their living room, which explains the reason why the average recorded temperature is still above the minimum threshold of 18 °C. Instead, they stopped running the heating system in the spaces they did not use. There is no data to examine the impact of energy prices on indoor temperatures in Case 05. However, participants reported in the interview that they significantly reduced running their heating system and the dwelling was overly cold during winter. The interviewee stated '*Because the more we leave it on the more we will waste gas, which is more expensive. The problem is we had a limited time to leave it on, for example, no more than 20 min due to prices, three to four times a day*'.

4.4. Thermal comfort & energy prices

Collected comfort votes in the survey show that participants had varied thermal comfort requirements and experienced different thermal sensations. However, whilst a clear impact of running the heating system can be seen on indoor thermal conditions, there is no clear

Table 5
Air temperature in the living rooms of the examined cases as recorded during January-February 2023.

Average indoor conditions		Case 01	Case 02	Case 03	Case 04	Case 05	Case 06	Case 07	Case 08	Case 09
Hourly air temperature Jan-Feb 23	Percentage of instances air temperature below 18 °C	52	97	98	100	Value could not be determined. Data could not be retrieved from the datalogger.	39	96	7	1
	Average air temperature	18	11	15	14		18	16	20	20
Air temperature at 18:00	Percentage of instances air temperature below 18 °C	22	84	96	100		15	76	9	0
	Average air temperature	19	12	17	15		19	17	20	21

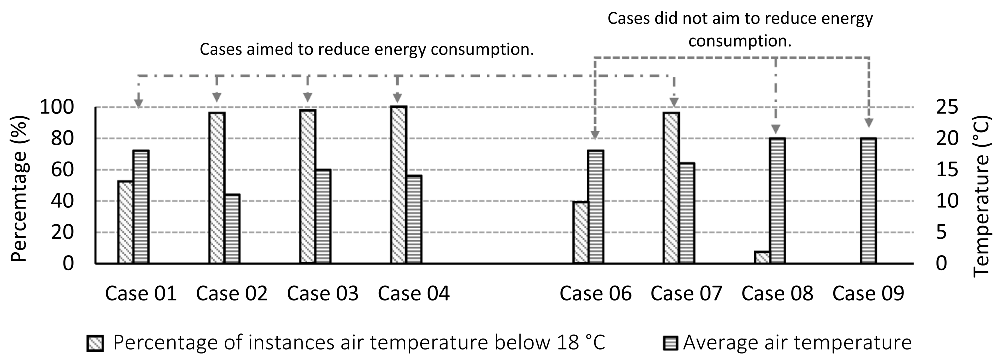

Fig. 5. Air temperatures in the living rooms of the examined cases as recorded in January-February 2023.

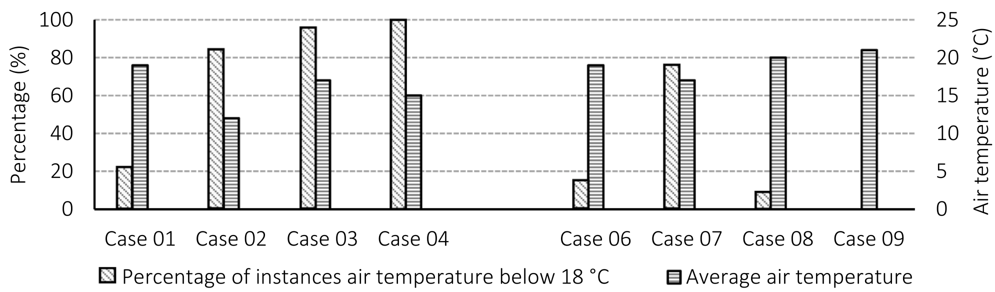

Fig. 6. Air temperatures in the living rooms of the examined cases as recorded at 18:00 in January-February 2023.

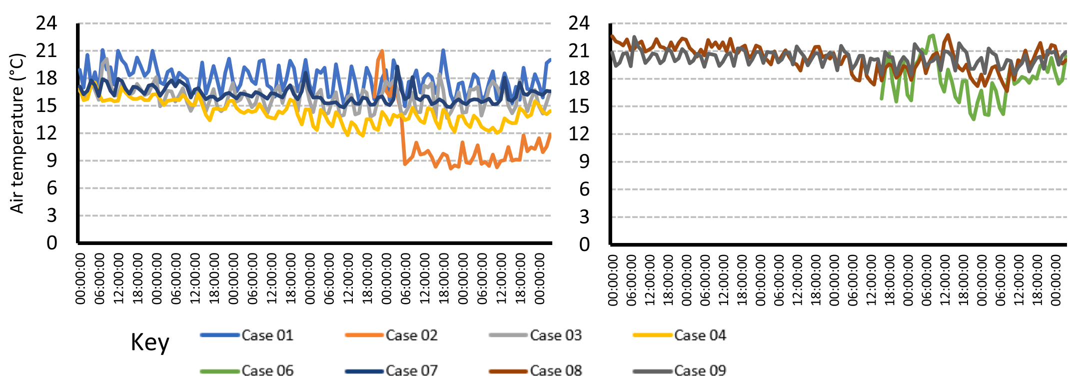

Fig. 7. Hourly air temperature in the living rooms of the examined cases during January 2023. Occupants aimed at reducing energy consumption (left), and occupants did not aim at reducing energy consumption (right).

correlation between the running of the heating systems and the thermal sensations and comfort of participants (Table 6; Fig. 8). The data of cases 01, 03, 06, 07, 08 and 09 shows that occupants were thermally comfortable during most of the time despite the fact they experienced different thermal conditions. However, their thermal comfort requirements were different (Table 6, Figs. 9 and 10). The average comfort temperature, for thermal sensations ranging between −1 and +1, in cases 02, 03 and 07 ranged between 12 °C and 16 °C whilst it was 18 °C–20 °C in cases 01, 06, 08 and 09. The neutral temperature in cases 02, 03, and 07, at which the thermal sensation vote is 0, is in the temperature range of 15 °C to 18 °C, and it ranged between 17 °C and 23 °C in the other group of cases. The occupants of Case 04 reported zero thermal comfort votes and their thermal sensations were cold during the surveyed period. Figs. 9 and 10 demonstrate that the thermal comfort requirements of participants are affected by the thermal conditions of their surrounding environments. For the same outdoor temperature, the

Table 6
Thermal sensations and comfort air temperatures of participants during January–February 2023.

Thermal sensation and comfort	Case 01	Case 02	Case 03	Case 04	Case 05	Case 06	Case 07	Case 08	Case 09
Lowest comfort air temperature (°C)	16	11	14	NA		17	15	17	18
Average comfort air temperature (°C)	18	12	16	NA		19	16	20	20
Percentage of comfort votes (%)	84	66	94	0	30	100	90	96	100

Note: Thermal comfort votes included the votes for the thermal sensations slightly hot (+1), comfortable (0), and slightly cold (−1).
Cases 01, 02, 03, 04, 05 and 07: aimed to reduce energy consumption.
Cases 06, 08 and 09: did not aim to reduce energy consumption.

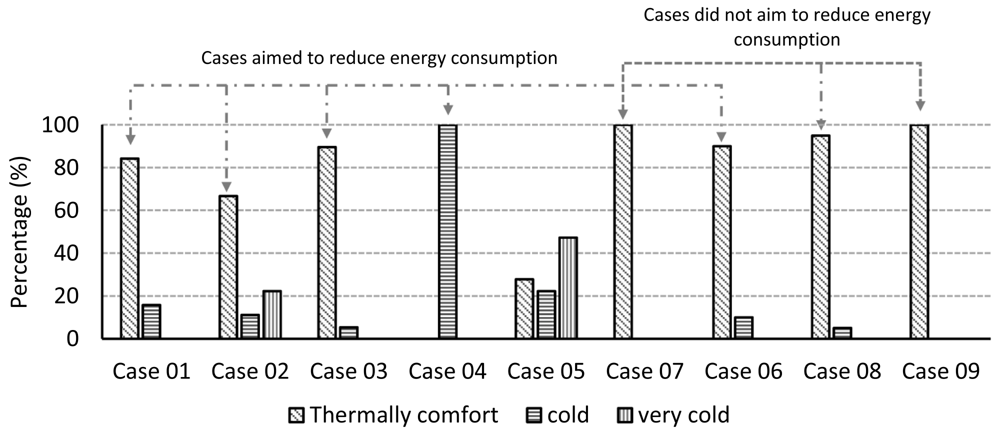

Fig. 8. Percentages of the thermal comfort votes of the study participants in January – February 2023.

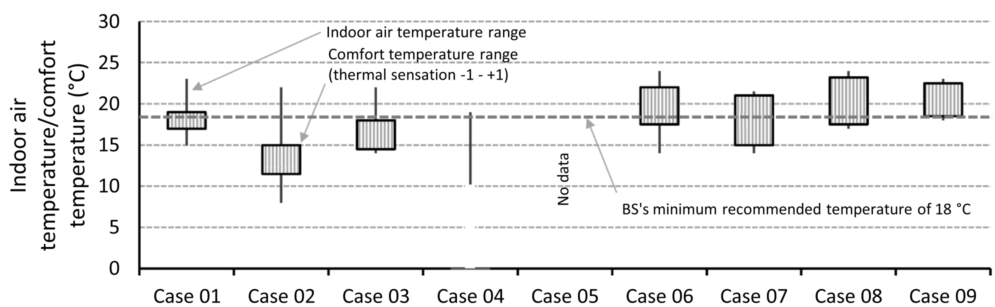

Fig. 9. Relationship between indoor air temperatures and thermal comfort votes in the examined nine cases.

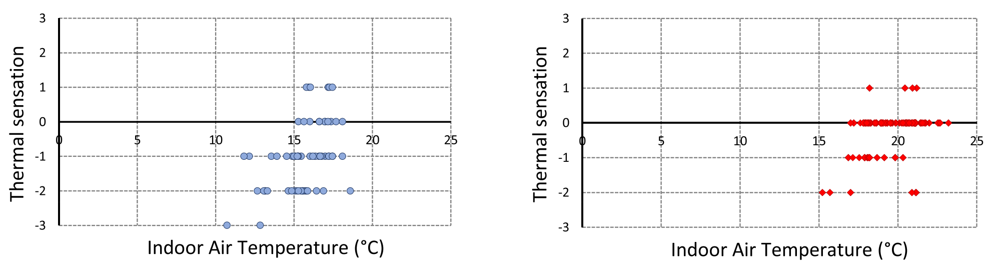

Fig. 10. Regression analysis of indoor air temperature and thermal sensation showing the neutral temperature ranges in cases 02, 03, 04 and 07 (Left) and in cases 01, 06, 08, and 09 (Right).

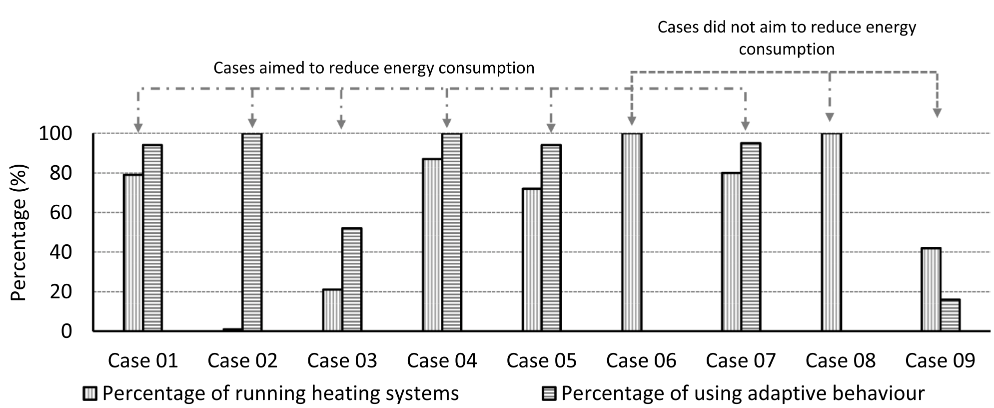

Fig. 11. Percentages of using heating systems and adaptive measures to maintain thermal comfort.

lower the temperature in the surrounding indoor environment the lower the thermal comfort temperature. Participants of cases 01, 02, 03 and 07 were comfortable at temperatures below the minimum recommended threshold of 18 °C.

To achieve thermal comfort, participants reported using heating systems and adaptive measures. In all nine cases, windows were reported closed for all or most of the time to preserve heat. Cases 01, 02, 03, 04, 05 and 07 show a high level of dependence on using adaptive measures to maintain thermal comfort. Occupants of cases 06, 08 and 09 depended on running heating systems to achieve thermal comfort (Fig. 11). Collected data shows that increasing clothing layers and using blankets were the primary behavioural measures employed by participants to achieve thermal comfort (Fig. 12). The adoption of these behavioural measures was triggered by the first received winter energy bills which made participants more aware of the financial implications of rising energy prices on their domestic budgets. This was particularly stressed in the interviews by the participants of cases 04 and 07.

Data demonstrates that adopted behavioural measures allowed participants to maintain a level of thermal comfort whilst reducing their energy consumption. Fig. 13 shows a comparison in the gas consumption as per energy bills provided by the participants of four cases during the interviews. Cases 06 and 09 show increases in energy consumption of 40 % and 47 %, respectively between 2022 and 23. In these two cases, participants did not aim to reduce energy consumption, but run heating systems to satisfy their thermal comfort requirements. Increased energy consumption in these two cases could be partly due to lower outside temperatures. In Case 06, the average outdoor temperature in December 2022 was 2.9 °C lower than in December 2021. Similarly, in Case 09, the average temperature in February 2023 was 7.8 °C, which was 1.2 °C lower than in 2022. As a result, occupants in both cases consumed more energy to counteract the colder conditions and maintain thermal comfort [58,59]. In cases 03 and 04, in which participants aimed to reduce their energy consumption and used adaptive measures to achieve thermal comfort, reductions in energy consumption of around 27 % were achieved between 2022 and 2023. However, participants reported that, due to the surge in energy prices, despite reducing their energy consumption, their energy bills were still higher than in previous years. According to provided energy bills by participants for this study, energy tariffs increased by 56 % for electricity and 148 % for gas between 2021 and 2022/23.

4.5. Statistical analysis results

Table 7 shows the results of the undertaken statistical analysis. There is a positive and statistically significant correlation (P-Value < 0.05) between indoor temperature and participants' thermal sensations. The higher the indoor temperature the higher the thermal sensation. The statistical analysis shows a negative and significant correlation between outdoor temperature and participants' thermal sensations. The lower the outdoor temperature the higher the thermal sensation. This is irrational, and it results from participants increasing indoor temperature when the outside temperature decreases. In other words, the analysis does not catch the impact of outdoor temperature on participants' thermal sensation but the impact of indoor temperature.

Statistically, there is a negative and statistically significant correlation between adopting behavioural measures to achieve thermal comfort and indoor temperature. The lower the indoor temperature, the higher the intensity of adopting behavioural actions to achieve thermal comfort. The analysis shows a negative and significant correlation between comfort temperature and the intensity of using adaptive measures. There is a positive and statistically significant correlation between the indoor air temperature and the average comfort temperature of participants. The higher the indoor temperature, the higher the average comfort temperature.

The results of this statistical analysis support concluded associations between indoor temperatures, affected by running the heating systems and the high prices, participants' thermal comfort requirements and their tendencies to use adaptive behavioural measures to achieve thermal comfort. They show that the thermal sensation of people is more affected by indoor conditions than outdoor conditions, and that high levels of using adaptive measures are associated with low comfort temperatures and low indoor temperature contexts.

5. Discussion

The findings of this study offer some of the latest insights into indoor thermal conditions and energy-related behaviours in UK houses during challenging times. Although the study examined a relatively small number of cases (nine houses), it provides a comprehensive analysis of both quantitative and qualitative data, and the findings are statistically evidenced.

Results demonstrate that the increases in energy prices have had a significant impact on indoor thermal conditions in homes. Four cases out of the nine examined cases show that occupants experienced colder conditions than the national averages recorded during the pre-energy-crisis periods. The average daily air temperatures in these cases ranged between 11 and 16 °C, whilst the recorded average daily air temperature ranged during the previous four decades between 17.5 and 21.6 °C (Table 1). The results show that households were unable to run their heating systems to satisfy their comfort requirements due to the high energy prices. This was particularly stressed during the interviews. These findings agree with the studies and media reports about the impact of the energy crisis on households' abilities to run their heating systems [8,11,20].

The findings of this study also agree with the results of other studies that examined the responses of building occupants towards increases in energy prices in the UK and other countries [60,61]. This study showed that out of nine examined households, six were concerned about the increases in energy prices and took actions to reduce their energy consumption. Similarly, Zapata-Webborn et al. [11] showed that households, in the UK, on average, reduced their energy consumption by up to 10.8 % in comparison to previous years. Out of 2710 surveyed individuals, 99 % reported making '*great*' or '*some*' efforts to save energy. Einolander et al. [2] investigated the impact of the recent global energy

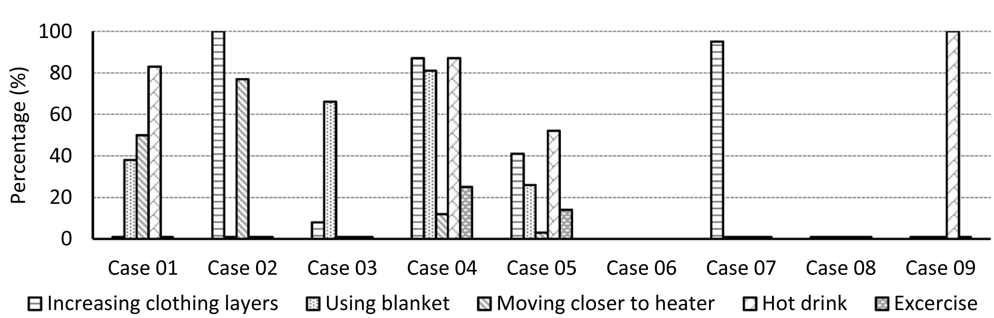

Fig. 12. Used adaptive measures to achieve thermal comfort.

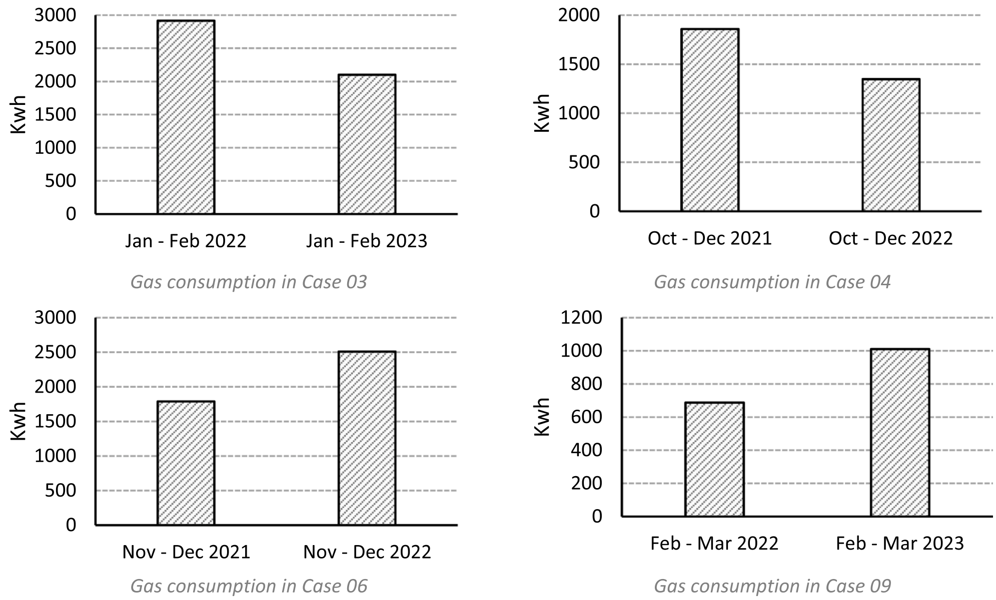

Fig. 13. Gas consumption between 2021 and 2023 in four of the examined cases.

Table 7
Statistical analysis results.

Statistical Test		Indoor air temperature	Outdoor mean air temperature
Thermal sensation	Pearson correlation	+0.317	−0.212
	Sig. (P-value)	0.000	0.002
		Average comfort temperature	Average indoor air temperature
Percentage of using behavioural actions	Pearson correlation	−0.785	−0.779
	Sig. (P-value)	0.021	0.023
		Average indoor air temperature	
Average comfort temperature	Pearson correlation	0.971	
	Sig. (P-value)	0.000	

crisis on energy consumption behaviour in Finland. It examined the behaviours of 400 households in the country, and it found that households reduced their energy consumption by over 15 % due to the increases in energy prices. Elnaklah et al. [62] presents the case of Jordan, in the Middle East, in which the energy consumption was reduced by around 50 % in commercial buildings following a governmental decision to increase energy tariffs.

This present study highlights the adaptation capabilities of building occupants and shows that their thermal comfort requirements vary. Participants used a range of adaptive measures to maintain a level of thermal comfort whilst reducing energy consumption. These adaptive measures included increasing clothing layers, turning off heaters in not used spaces and using blankets, which are in line with adopted behavioural measures by households across the UK as reported by [11,58]. The adopted behaviours of using a blanket or increasing clothing layers are highly rational. The thermal insulation of clothing is one of the main effective factors on the thermal sensations of building occupants, which is measured in thermal comfort literature using the 'clo' value. Wearing additional layers of clothing and using a blanket enhance personal insulation, and consequently reduce heat loss, keeping individuals warm [27,30,45].

The results of this study also demonstrate that the thermal comfort requirements of building occupants are affected by their surrounding conditions, which agrees with the theory and principles of the adaptive thermal comfort model [44,63]. However, challenging the adaptive thermal comfort approach of associating thermal comfort limits with outdoor conditions, the analysis of this study shows that the thermal comfort requirements of people are more affected by their direct surrounding indoor thermal conditions than outside conditions. For the same outdoor conditions, the participating households of this study reported different neutral and average thermal comfort temperatures (Table 6, Figs. 9 and 10). Similar results were reported by [64] in which it was found that occupants, in the Middle East, exhibit different thermal comfort thresholds, influenced primarily by indoor air temperature variations rather than external thermal conditions.

The results of this study do not suggest that it is safe and acceptable for building occupants to live in spaces where air temperatures are below the recommended threshold of 18 °C. Although this study presents participants reporting high levels of thermal comfort while experiencing low indoor temperatures in their homes, the investigation of this study did not include examining their mental and physical health. It has been reported by literature that building occupants living in cold homes are subject to increased risks of having mental and physical health problems [14,15]. The UK Cold Weather Plan suggests that air temperatures below 16 °C increase risks of respiratory illnesses, and temperatures ranging between 9 °C and 12 °C could lead to high blood pressure and cardiovascular disease [65].

6. Scope and limitation

This study investigated the impact of the increases in energy prices during the winter of 2023 on indoor thermal conditions in homes and occupants' capabilities to maintain their thermal comfort. The concluded impact of energy prices on indoor conditions and occupants is evidenced in this study. However, it is important to state that there are other factors that could affect indoor thermal conditions in buildings and occupants' thermal sensations that are not investigated in this study. These include the building fabric and design, occupants' characteristics and behaviours, climatic factors, and building services. This research acknowledged the impact of these factors by examining diverse cases, but examining the specific impact of these factors is outside the study scope. This study did not aim to examine the impact of these factors on the thermal sensations of participants and indoor thermal conditions.

This article provides energy consumption data from four out of nine cases to illustrate how occupant behaviour and energy-saving attitudes contribute to reducing energy use. However, similar to the highlighted point above, energy consumption in buildings is affected by factors other than occupant behaviours, including outside conditions, the insulation level of buildings and the efficiency of service systems. This study used cases of different features to enhance the reliability and representativeness of its results, but it did not aim to examine the specific impact of these factors on energy consumption.

The undertaken fieldwork was in and around the city of Plymouth, to the southwest of the UK, and it covered nine cases. Considerations were taken to conclude with reliable results that could represent the whole country, especially with regard to people's attitudes towards reducing their energy consumption and using thermal adaptive measures. However, reported indoor thermal conditions in this study may not represent the rest of the country. The South West England region of the UK is relatively warmer than other regions. Also, all the examined cases were of employed people with stable incomes. This study did not examine cases where occupants are under severe financial constraints.

7. Conclusions

This study investigated the impact of the energy crisis during winter 2023 on indoor thermal conditions in homes and households' abilities to satisfy their thermal comfort requirements. Undertaking research work involved recording indoor thermal conditions in nine houses alongside conducting a thermal comfort survey and interviews.

The results of this study demonstrate that the increases in energy prices have negatively affected households' abilities to heat their homes during winter 2023. Out of nine households that participated in the survey, six had to reduce running their heating systems to cut their energy bills. Four of these households experienced air temperatures below the recommended threshold of 18 °C for most of January and February. The thermal comfort survey and the interviews revealed that, whilst reducing the running of their heating systems, building occupants used adaptive measures to maintain a level of thermal comfort. The thermal comfort requirements of building occupants vary, and they are significantly affected by indoor thermal conditions. The average comfort temperature ranged in the examined cases between 12 and 20 °C.

This study shows that the energy crisis and the high living costs have forced some households to live in cold residential spaces that could negatively affect their health and wellbeing. The investigation of this study evidence that utilising adaptive measures could help with reducing energy consumption and maintaining thermal comfort. However, further research is needed in this field. In particular, this study recommends undertaking research studies investigating the adaptation extent of building occupants, and the specific impact of the wide range of adaptive measures on their thermal sensations and energy consumption.

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CRediT authorship contribution statement

Omar Al-Hafith: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Satish BK:** . **Pieter de Wilde:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Omar Al-Hafith reports financial support and equipment, drugs, or supplies were provided by University of Plymouth. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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