Investigating the impact of communal heating charges on internal temperature profiles, thermal expectation and excess in energy demand

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Abstract

Reducing energy demand in dwellings is an important component of meeting carbon reduction targets. The drivers of this demand are linked to occupant practices, varying greatly between people and locations. Heating, as the main component of energy demand in dwellings in the UK, is often associated with thermal comfort, defined in ASHRAE 55 as the 'condition of mind which expresses satisfaction with the thermal environment'. How do people fulfil that condition in their homes? What is deemed as reasonable or excessive thermal comfort practice? This paper explores how residents living in social housing blocks are heating their homes and to what extent their practices may be influenced by heating charges. This study is focusing on three social housing buildings located in Portsmouth, two with communal heating charges (blocks A and B) and one without (block C). Using a mixed-methods approach, data were collected using environmental monitoring, semi-structured interviews and questionnaires. Results show that there is a relationship between the indoor air temperature profiles in living room and communal heating management strategy and the choice of individual heating control settings. This implies that the low-cost heating supply to some occupants may have led to constantly high indoor air temperature, which in turn may result in thermal adaptation to these high temperatures and raise occupants' thermal expectations. On the other hand, occupants in the building without communal heating charges appear unable to afford the high costs of heating in their poorly insulated homes. The conclusions point out that an on-site informed assessment of established occupancy conditions and practices should precede any decisions on energy efficiency measures, as simplified, generic occupancy related assumptions usually disregard such important thermal comfort related processes.

Key words: Indoor air temperature, winter, social housing, heating patterns, thermal expectation, adaptive thermal comfort

1. Introduction

In 2014 the domestic sector accounted for 27% of UK's final energy consumption (DECC, 2015a). Heating energy has overall been declining due to milder winters, an uptake of energy efficiency improvements since 2004 (DECC, 2015b) and higher energy costs (Summerfield et al., 2010). However, space heating remains the largest contributor of domestic energy use at 62% (Palmer & Cooper, 2013), which means that it is an important area for energy reduction in order to meet the ambitious carbon targets of the UK Government to reduce carbon emissions by 80% by 2050 from the 1990 baseline (UK Parliament, 2008).

Household heating energy use is primarily influenced by the occupants' demand temperature (Firth et al., 2010) and heating use patterns (Huebner et al., 2013). Modelling results have suggested an increase of 4 ^{o}C of the average indoor temperature in winter over the last forty years (Palmer & Cooper, 2013), whilst measurement data have indicated an even more striking increase of up to 1.3 ^{o}C per decade from 1978 to 1996 (Mavrogianni et al., 2013). This highlights a risk of increasing heating demand trends associated with higher standards of comfort. Future indoor temperature trends are particularly important considering the updated projection of an increase in domestic emissions of 5 % over the next 20 years due to expected rises in household numbers (DECC, 2015c). Therefore, a better understanding of the parameters, which influence internal temperatures and their long-term trends, appears to be necessary.

Further to the above, domestic modelling tools such as BREDEM currently use standard assumptions both for the demand temperature (set-point temperature) and the occupant heating pattern (Henderson & Hart, 2015). More specifically, BREDEM assumes a demand temperature of 21 ^{o}C for the living room and 18 ^{o}C for the rest of the house (BRE, 2013). In terms of heating pattern, a typical schedule for the living room includes nine hours of heating on weekdays (07.00-09.00 and 16.00-23.00) and 16 hours on weekends (07.00-23.00) (Huebner et al., 2015). However, studies have found deviations from these assumptions both in heating levels (Oreszczyn et al., 2006; BRE, 2013; Huebner et al., 2013; Kane et al., 2015; Teli et al., 2015) and profiles (Huebner et al., 2015).

Parameters that have been found to influence internal temperatures in homes leading to variations between households include socio-demographic variables, tenure, building type, construction properties and type of heating system (Hunt & Gidman, 1982; Oreszczyn et al., 2006; French et al., 2007). This paper investigates the influence of the heating charging approach in three social housing buildings with similar overall socio-demographic conditions, building properties and fitted heating systems.

2. Study design

The study is investigating the impact of communal heating charges on energy demand in three high-rise social housing buildings located in Portsmouth (UK). The tower blocks are owned and managed by the local authority Portsmouth City Council (PCC). Two of the blocks have communal heating charges (blocks A and B), whereas tenants pay a small charge for heating through the rent and the rest is paid by PCC. In block C tenants are individually billed according to their electricity consumption. Built in the 70's, the three case study buildings have similar external wall properties with an estimated heat transfer coefficient (U-value) of 1 W/m^{2}.K for the external walls. The U-value of the walls exceeds current building regulation limits by a factor of 3 (NBS, 2014). This is expected to have a significant impact on the building heat losses (for details on block C, see Teli et al., 2015). The heating systems rely on a combination of electric storage heaters with underfloor heating in blocks A and B, and electric storage heaters in block C. PCC have opted for Economy 7 tariff, enabling storage heaters to be charged at night at a lower tariff. However the combination of night storage heaters with underfloor heating in blocks A and B has led to additional twice a day charging of the storage heaters, due to complaints for insufficient heating from tenants in flats with underfloor heating. Furthermore, how occupants of block A and B choose to heat their flats has no direct connection with their rental change. Currently PCC shares the heating bill per m^{2} across their building stock. This ensures fairness in that a tenant in an old building is not at financial disadvantage compared to a new building tenant. Therefore, blocks A and B benefit from sufficient low-cost heating, compared to block C where tenants bare the potentially high cost of their electric storage heaters' consumption. These two heating charging conditions are very different despite the fact that all buildings are similar, poorly insulated buildings with low or no income tenants.

Applying a mixed-method approach, data were collected using occupant thermal comfort surveys in the form of in situ semi structured interviews and questionnaires, and building environmental monitoring (air temperature and relative humidity). Using a convenience sampling strategy, 39 flats were monitored during the heating period (N=39); 18 flats in block C (4 weeks monitoring, from the 23rd March to the 19th April 2013) and 21 flats in blocks A and B (6 weeks monitoring, from the 15th February to the 28th March 2014). Hourly external weather conditions were retrieved from a local weather station (IENGLAND451) that reports the measurements online to an open-access database (Wunderground, 2016). During the two studied periods, the daily mean external temperatures (T_{ext}) averaged 8.7°C (σ = 1.7 °C), which is below the degree-day threshold of 15.5 °C and low enough for the buildings to require significant space heating (CIBSE, 2006). MadgeTech RHTemp101A dataloggers were used to measure indoor air temperature (T_a) and relative humidity (RH) with 5-minute intervals in blocks A and B and 3-minute intervals in block C. The dataloggers recorded (T_a) at a 0.01 °C resolution and (RH) at a 0.1 % resolution; based on logging memory, battery duration and the objectives of this study. The manufacturer stated accuracy is +/- 0.5 °C for T_a and +/- 3 % for RH, which is within the recommendations of ISO standard 7726 (ISO, 2001). The dataloggers were placed in the living room and the main bedroom of each flat, close to the participants' place of typical activities and away from any direct heat sources

The semi-structured interviews and the questionnaire survey were carried out in the autumn of 2014 during the heating season. The interviews in blocks A and B were conducted by the Sustainable Energy Research Group of the University of Southampton, whilst PCC interviewed a random sample of 76 tenants in block C. Most of the surveyed flats in blocks A and B were single occupancy dwellings and most of the participants were over 55 years old. Participants reported to have occupied the specific flats for 10 years on average (σ = 9.5 years). In all cases, the main room used was the lounge with an average time spent in the flat of 17 hours (σ = 6 hours) including sleeping time. Most interviewees in blocks A and B were in general satisfied with the thermal environment of their flats throughout the year. With regard to block C, a surprising one third of the interviewees reported that they never use the storage heaters; with the most frequently reported reason being the high running costs (Teli et al., 2015). Furthermore, 67% of the respondents stated using secondary heating in the form of portable plugin electric heaters. Half of these households using heaters reported these as their main heating source. These occupants' characteristics and their reported heating usage are reviewed in the results section.

With regards to the analysis method, only data collected in living rooms were used to review indoor air temperature profiles. The two datasets ([blocks A and B] and [block C]) were re-sampled at 15-minute intervals. For each flat the observations were screened for outliers, the exclusion criteria was defined as 1.5 times the interquartile range above the upper quartile and bellow the lower quartile. Only 1.5% of the observations were identified as outliers and were excluded from subsequent analysis. First a cluster analysis of (T_a) was undertaken to identify typical weekday and weekend day profiles following the method described in Huebner et al. (2015). The analysis consisted of 672 inputs; including 7 days with 96 (T_a) measurement points each. To determine the number of clusters

Ward’s method (1963) was applied with a threshold of 0.8 for the approximately unbiased *p*-value and a minimum cluster size of three dwellings. Once each flat was associated to a cluster, the mean (T_a) for each cluster was estimated and used in the second part of the analysis, which reviewed the variations in (T_a) levels between [blocks A and B] and [block C].

3. Results

From the hierarchical cluster analysis, three clusters were identified for both datasets. Figures 1 and 2 show weekday and weekend diurnal indoor air temperature profiles for each dwelling and the mean temperature of all dwellings within each cluster.

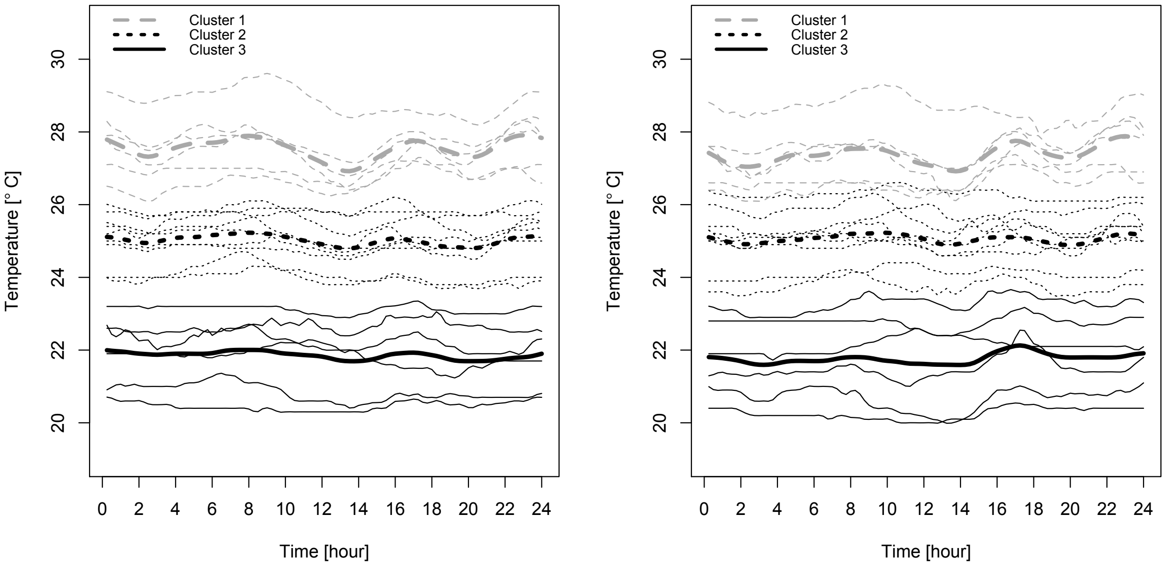

Figure 1. Dataset 1, heating bill included [blocks A & B] Living room daily mean air temperature profiles and average air temperature profiles of the three clusters for weekdays (left) and weekend days (right) (note: T_a range from 19 to 31 °C)

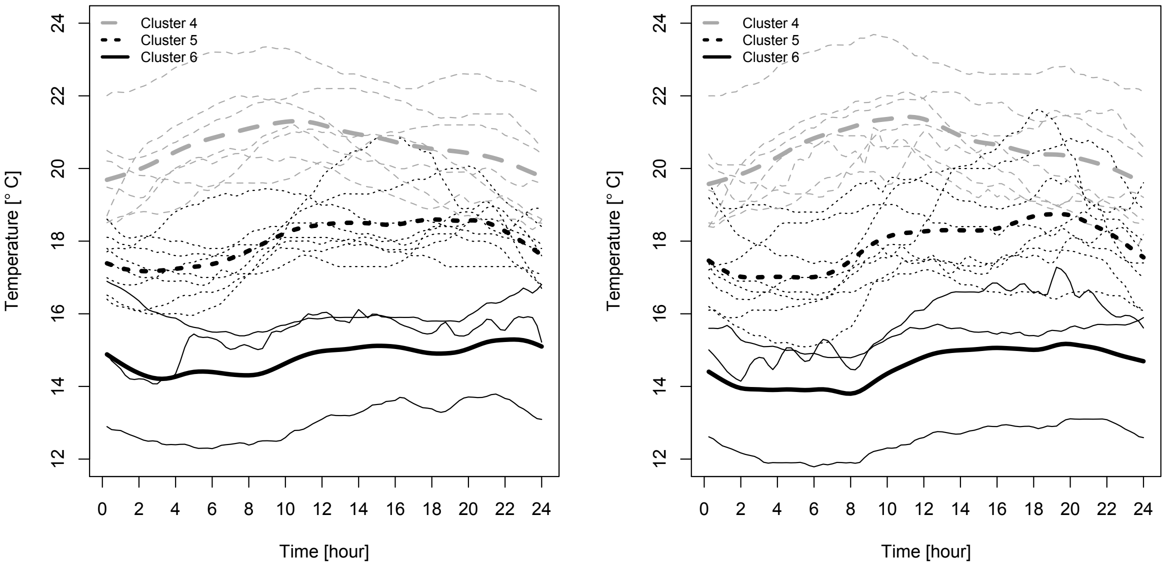

Figure 2. Dataset 2, heating bill separate [block C] Living room daily mean air temperature profiles and average air temperature profiles of the three clusters for weekdays (left) and weekend days (right) (note: T_a range from 12 to 24 °C)

As shown in Figure 1 and 2, occupants in blocks A and B experienced much higher temperatures in their lounges compared to those in block C, with the exception of clusters 3 and 4. In blocks A and B daily mean air temperatures during weekday ranged from 20.3 ^{o}C to 29.6 ^{o}C (ΔT = 9.3 ^{o}C), while in block C temperature ranged from 12.3 ^{o}C to 23.4 ^{o}C (ΔT = 11.1 ^{o}C). While daily mean temperature differences between the lowest and highest recordings (ΔT) are similar for the two datasets, the absolute temperature levels are very different. This may be attributed to the different way the heating systems are operated; as occupants in blocks A and B use their storage heaters, while occupants in block C are switching them off and use secondary electric heaters 'on demand', i.e. when it is very cold, in order to reduce the heating costs (Teli et al., 2015).

Reviewing the first dataset [blocks A and B], Cluster 1 (N=6) shows *'three peaks'*; the first temperature rise starting about 3am and finishing about 9am, the second one starting about 1pm and finishing about 5pm, and the last one starting about 8pm and finishing about 11pm. These peaks coincide with the times when PCC turns on the heating in blocks A and B. These peaks suggest that the control settings on the storage heaters are set to maximum; therefore instead of only recharging, the heaters release heat almost immediately, which also explains the high monitored temperatures levels. Cluster 2 (N=9) and Cluster 3 (N=6) show little variations throughout the course of the day, suggesting that either these flats are fitted with underfloor heating or the controls on the storage heaters are set at medium and constant levels. These clusters will be referred to as *'flat line'*. With regards to the second dataset [block C], Cluster 4 (N=7) shows a steady rise in temperature from 00:00 to 11:00 it will be referred to as *'morning risers'*. Cluster 5 (N=8), referred to as *'daytimers'*, shows an increase in temperature from 3am to 11am, then little variations until 8pm when temperature then decreases. The mean temperature in this cluster is relatively low (18 ^{o}C), these homes operate a critical level of heating during occupied daytime. Finally Cluster 6 (N=3), referred to as *'steady rise'*, shows some variations but overall the temperatures are low (average 14.8 ^{o}C), therefore it can be assumed that there is either limited or no heating in these flats. The steady rise in temperature may be attributed to internal and solar gains. In summary, these 6 clusters indicate diverse heating levels and patterns, which maybe liked to *"energy personalities"* (Mooney, 2015). In this study, the *"energy personalities"* may be less related to lifestyle choices but to financial circumstances, type of heating systems, controls and different management strategies. In block C, the cost of heating may constrain the way occupants heat their homes, as fuel poverty is an issue. In contrast in blocks A and B, operating the heating system may be an issue.

The standard deviation is an indicator of the variation within each cluster. Both *'flat line'* clusters have the smallest standard deviation; dwellings associated with these clusters are most likely to have constant heating with set levels for input/output heat flow. The *'daytimers'* have the largest standard deviation; dwellings associated with this cluster are most likely to have longer on-off heating cycle and set to a low heat output level. Early temperature rise in *'morning risers'* and daytime temperature rise in *'daytimers'* may be attributed to either programmed timer or manual control; whilst variations in *'steady rise'* is most probably related to the weather variations and incidental heat gain from occupancy (e.g. cooking), as these flats have either limited or no heating. Overall, the three clusters with communal heating charges, blocks A and B, have the smallest standard deviations, maintaining fairly constant temperatures. The three clusters in block C have higher standard deviations, which is related to occupants switching off storage heaters and using secondary electric heaters in an effort to manage running costs.

Table 1. Living room daily air temperatures mean, maximum, minimum and standard deviations for weekdays (wk) and weekend days (we) in the six clusters (^{o}C)

Blocks	Number of flats	Clusters no. and name	Mean (μ) and associated (σ)		Minimum		Maximum		Standard deviation (σ)	
			wk	we	wk	we	wk	we	wk	we
A and B (heating bill included)	6	1 *'three peaks'*	27.5 (0.7)	27.4 (0.8)	26.9	26.9	27.9	27.9	0.3	0.3
	9	2 *'flat line 1'*	25.0 (0.7)	25.1 (0.8)	24.8	24.9	25.3	25.3	0.1	0.1
	6	3 *'flat line 2'*	21.9 (1.0)	21.8 (1.2)	21.7	21.6	22	22.2	0.1	0.1
C (heating bill separate)	7	4 *'morning risers'*	20.6 (1.1)	20.6 (1.1)	19.7	19.6	21.3	21.5	0.5	0.5
	8	5 *'daytimers'*	18.0 (0.5)	17.9 (1.0)	17.1	17.0	18.6	18.8	0.5	0.6
	3	6 *'steady rise'*	14.8 (1.6)	14.5 (1.8)	14.2	13.7	15.3	15.3	0.4	0.5

The second part of the analysis reviews the daily mean air temperature for each cluster. These data are normally distributed (Shapiro-Wilk test, $p > 0.05$), and each group of clusters have homogenous variances (Levene's test, $p > 0.05$). One-way ANOVA was used for multiple unpaired group comparisons, and the Tukey's post-hoc test was used for pairwise comparisons. For both datasets [blocks A and B] and [block C], the daily mean air temperatures were significantly; [blocks A and B] weekdays ($F(2,18)=76.27$, $p=1.6e-9$), [blocks A and B] weekends ($F(2,18)=59.35$, $p=1.2e-8$), [block C] weekdays ($F(2,15)=8.63$, $p=1.2e-6$) and [block C] weekends ($F(2,15)=27.86$, $p=8.9e-6$). Post-hoc pairwise comparisons between clusters shows that daily mean temperatures were significantly different between all clusters in each group. These results are suggesting that the shape of the clusters may be linked to temperature levels. In other word, if other dwellings in Block C were monitored and their daily mean temperature was around 18 ^{o}C, it could be suggested that their heating pattern would be similar to the *'daytimers'*. Finally the daily mean temperatures between both datasets were significantly different during weekdays ($F(5,33)=142.9$, $p<2e-16$) and weekends ($F(5,33)=105$, $p<2e-16$). Post-hoc pairwise comparisons between clusters shows that daily mean temperatures were significantly different between all clusters with the exception of *'flat line 2'* and *'morning risers'* (weekday difference = 1.24 and $p=0.15$, weekend difference = 1.20 and $p=0.33$). In this particular case the shape of the two clusters may be linked to choice of heating control strategy. For the *'flat line 2'* cluster, inexpensive heating supply may have lead to the occupants choosing constant heating, while *'morning risers'* may have chosen on-off heating cycles with programmed timers or manual control.

4. Discussion and conclusions

The analysis developed in this paper enabled the study of occupants' heating pattern in 39 social homes, and uncovered five profiles '*three peaks*', '*flat line*', '*morning risers*', '*daytimers*' and '*steady rise*'. This indicates that the one assumed pattern used in modelling tools is not representative of the variation of actual heating profiles encountered in the stock, as previously highlighted by Huebner et al. (2015). However, the results here have shown a significant relationship between the shape of these profiles and the temperature levels, unlike the analysis of the homes investigated in Huebner et al. (2015), where no significant relationship was found between the clusters' average temperatures. Furthermore, the average temperatures in that investigation ranged only slightly, between 18.7°C and 19.5°C, whilst in this study it ranged between 14.5°C and 27.5°C. This highlights that in this study both the assumed profiles and demand temperatures would fail to reflect the actual conditions in the flats, where the heating patterns are significantly influenced by the applied heating charging strategy and occupants' financial conditions.

It is important to highlight that the standard deviations of all six clusters are relatively small (from 0.1 to 0.6 °C). This is associated with the two stages averaging process used in the analysis. In the first stage each flat daily mean temperature profile is determined, then in the second stage each cluster temperature profile is established. For example, during weekdays Flat 17 living room daily temperature profiles have standard deviations between 1.0 and 3.3 °C, while the daily mean temperature profile has a standard variation of 1.7 °C (see Figure 3, left). Flat 17 is part of cluster 5, which has a standard variation of 0.5 °C during weekdays. Yet the daily mean temperature profiles of the eight flats' in cluster 5 have standard deviations between 0.3 and 1.7 °C (see Figure 3, right). Despite of the clusters' relatively small standard deviations, this analysis attempts to capture important patterns in the data.

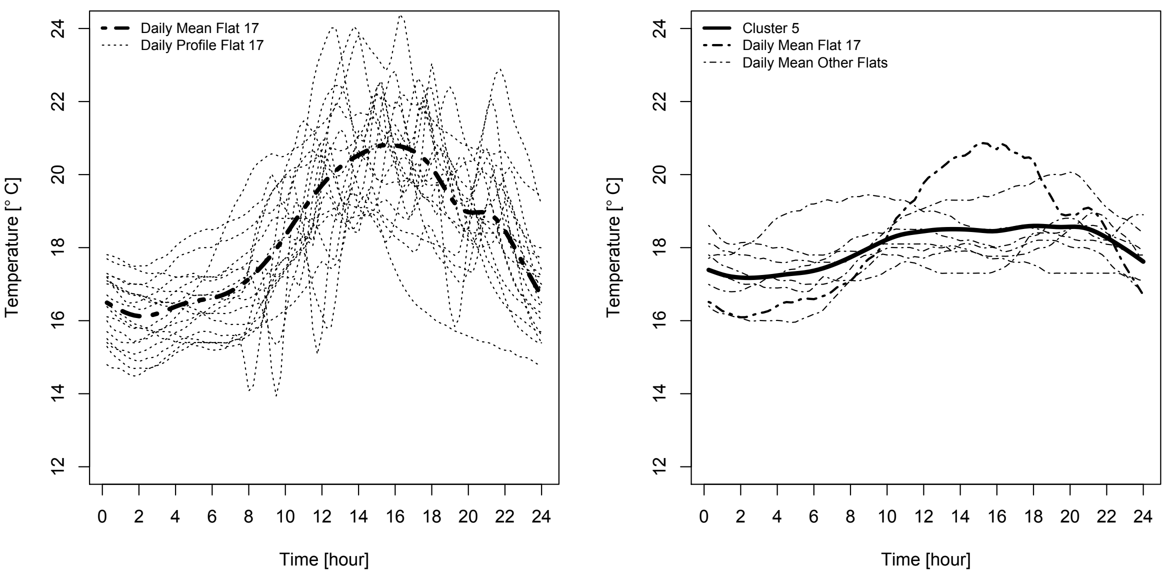

Figure 3. Weekdays - Flat 17 living room daily air temperature profiles and daily mean air temperature profile (left), Cluster 5 and associated flats living room daily mean air temperature profiles (right) (note: T_a range from 12 to 24 °C)

Further limitations of the study lay with the sampling strategy and data collection methods. Only one location was monitored in each room, however the spaces may be thermally heterogeneous, thus the temperature measurements may not be representative. The internal temperature profiles might be biased toward internal gains, solar gains and ventilation heat losses, and therefore may differ from heating profiles. The analysis reviewed in part the potential effect of all these inputs. Future studies may investigate the effect of flats' orientations between clusters. Furthermore this study's convenience sample is relatively small; participants may have similar attitudes and lifestyles. The findings are not representative but capture the variability in internal temperature profiles between heating management strategies. The study is located in the South-East of England; therefore the heating patterns may reflect specific geographical and cultural features.

This study shows that heating charges and associated occupant behaviours have a significant effect on the heating levels and patterns. For most flats with communal heating charges internal temperatures in living rooms were above the World Health Organization temperature guideline of 21^{o}C (2007), whilst for most flats without communal heating charges internal temperatures were below this guideline; in some cases worryingly below adequate levels (14^{o}C). This result suggests that communal heating charges combined with systems with unusual operation and controls (e.g. storage heaters) in poorly performing buildings may lead to excess in heating levels and therefore excess in energy demand. Furthermore heating charge has also a significant effect on heating patterns. Communal heating charges and lack of understanding of heating controls led to fairly constant internal temperatures in living room. In contrast, for flats without communal heating charges internal temperature had greater variations, following outdoor climatic variations, as occupants switched off their storage heaters in order to manage their running costs. In this study, communal heating charges led to excess in energy demand in block A and B, but on the other hand it ensured warmth to people who would not afford it otherwise in such energy inefficient buildings, as shown in block C.

Furthermore, occupants in blocks A and B may now be accustomed to high indoor temperatures as suggested by their responses in the interviews, leading to thermal expectations. This expectation, in combination with communal charging and the lack of understanding of heating controls, led to practices that maintain high internal temperatures, resulting in high energy demand for heating. To reduce this demand, one approach may be to revoke the communal heating charge. However, this may lead to residents adapted to high temperatures falling into fuel poverty. If such an approach is to be pursued, it should be combined with measures to alleviate fuel poverty, i.e. building envelope improvements and retrofitting of appropriate heating systems with thermostatic controls. Furthermore, any changes would need to take into account the occupants' adaptation to high temperatures and help them to gradually lower the temperature set-points until the adequate levels of warmth for comfort and health are reached.

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