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UNPACKING MID-SEASON HEATING DEMAND IN SOCIAL HOUSING

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ABSTRACT

The efficiency of residential heat supply systems is compromised when the heat load varies. Heat load variability is mainly rooted in space heating demand variations. Heating demand is expected to fluctuate the most during mid-season, as this is when users thermally adapt to warmer or colder weather, resulting in what is known as the "thermal adaptation lag". The aim of this paper is to investigate this weather variability during mid-season leading to fluctuations of heating demand that impact the efficiency of heat supply systems. Here we present research conducted within five high-rise social housing tower blocks located in he city of Southampton,United Kingdom. Heating to the tower blocks is supplied through gas boilers to heat exchangers installed in each flat. Monthly heating demand monitoring from 2013 to 2017 at flat level shows that: (a) the variability of the heating demand is higher in the period November to March and is related to temperature variation, (b) the amount of heat required by Heating Degree Day is not constant. The analysis identifies potential implications for engineers designing heat supply systems for social housing which contribute to reducing the performance gap between building design and use.

INTRODUCTION

In the UK, the energy consumption of domestic buildings represents 16% of its total energy demand with heating amounting to 60% of building energy loads (Palmer & Cooper, 2013).

In heat networks, load variability and intermittence in the demand are a result of factors such as: dwelling fabric and systems thermal performance, number of dwellings in the network, weather, system controls and occupant profiles including occupancy, thermal comfort, economic status and household composition (Gadd & Werner, 2013). Load variability decreases the efficiency of the system and is expected to be higher during mid-season months, when heating demand increases or decreases. This stresses the importance of analyzing the characteristics of heating demand during mid-season to identify aspects that may help reducing the inefficiency during this period.

Hence, understanding space heating demand and its variability helps towards increasing the efficiency of heat supply and reducing energy consumption. Additionally, it contributes to a more appropriate design and management of heating systems.

Heating load estimation

The methodology most used for estimating heating loads in UK buildings is the Government's Standard Assessment Procedure for Energy Rating of Dwellings –SAP (Building Research Establishment Ltd (BRE), 2014), which defines the heating period as eight consecutive months, from October until May. Hughes et al. (2016) compared this assumption against reported heating patterns in English housing in the Energy Follow up Survey (Building Research Establishment Ltd (BRE), 2013). The analysis showed that the duration of the heating season varies by household as most participants used their heating between four and seven months a year, and secondly most houses reported no heating usage during May.

Additionally, the Standard Assessment Procedure assumes the same temperature set point throughout the entire heating season, 21°C in living rooms and 18°C in other areas of a house (Building Research Establishment Ltd (BRE), 2016). A recent study by Huebner et al. (2015) reported mean living room temperature variations between 16°C and 22°C in winter. Furthermore, space heating loads are estimated based on Heating Degree Days derived from historical mean outdoor temperatures for each month and region of the UK (Building Research Establishment Ltd (BRE), 2014). This results in mean values of monthly heating demand with no indication of the range of the load across the month. Also, as a result of this analysis, heating loads are expected to be higher during winter months (December, January, February), when mean temperatures are lower, than during mid-season months (October, November, March, April, May). To the authors' knowledge, there is little to no analysis that considers temperature variation during mid-season and winter months. This work provides knowledge to plug this gap.

Heating demand & Thermal comfort

Heating demand is affected by occupants' comfort requirements which influence heating settings and patterns. Comfort standards such as ASHRAE Standard 55 or BS ISO 17772 provide fixed temperature settings for winter months to estimate HVAC loads. However, as thermal comfort is dependent on weather, more specifically in recent outdoor conditions (Peeters, et al., 2009), adaptive models for heating may be applied instead of establishing the same limit for the entire season (Nicol & Humphreys, 2002; Nicol, 2017). This would contribute to profiling heating and its variability more accurately.

Efficiency of heating systems

Within the UK's domestic buildings, the majority (92%) have central heating systems, of which 63% are supplied by gas condensing boilers (Ministry of Housing, Communities & Local Government, 2018). The efficiency of this type of boiler varies seasonally based on the return temperature of the system, which is determined by the temperature required in the heat emitters (e.g. radiators). Based on this in the beginning of autumn and end of spring, emitters operate at lower temperatures, hence return temperatures are lower, and efficiency is higher. In winter months, emitters need higher temperature, return temperatures being higher and efficiency lower (Building Research Establishment Ltd (BRE), 2016).

Another factor that affects the efficiency of gas boilers is load variability. The maximum efficiency of a boiler is reached at maximum loads, operating at part load means a decrease in the performance of the system (Building Research Establishment Ltd (BRE), 2016). If a boiler is the main and only heating system in a building, it will be sized to meet peak loads, which are expected to occur during winter months and part loads during mid-season. Furthermore, variable loads can lead to intermittent switching of the boiler, which results in a decrease of the efficiency. Analyzing the heating demand during mid-season would allow for a more appropriate and accurate evaluating of a system's performance.

When designing building heating systems where multiple dwellings are served, the efficiency of the heat supply will be affected by the demand lag (Hayton & Shiret, 2009). This means that because the heating pattern will not be the same in all dwellings, peak load will not occur at one instant in time but lagged. A lagged load is also known a diversified one, and the smaller the number of buildings in a network, the more diversified it is. In a heat network, it is better to serve a large number of dwellings to have more uniform distribution of the heat demand. Heating patterns are expected to be more homogeneous in heat networks of domestic buildings with multiple dwellings than in commercial ones (Gadd & Werner, 2013).

Social Housing

Social housing is defined as affordable housing for people on a low income (Department for Communities and Local Government n.d.) and represents around 17% of building in England, UK. Social housing developments are mostly owned and managed by local City Councils who aim to meet occupant's thermal comfort in an efficient and affordable way. Based on its definition, social housing hosts economically restrained residents. This may affect their heating usage, as some people may adapt to lower temperatures to save on their heating bills (Dimitriou, et al., 2014), leading to heating loads different from what expected from the average UK household data. Such financial limitations of residents add importance to being able to efficiently deliver heat and design a system that meets the particularities of its demand.

This paper focuses on the analysis of the heating demand for a group of five identical social housing tower blocks located in the city of Southampton, UK. In particular, the research provided analysis of the space heating demand in mid-season and winter months based on heating records from 2013 to 2017. The buildings as the case study are presented highlighting their most important characteristics; secondly in the Methodology section, the procedures for cleaning and analyzing the dataset are explained; finally results of the analysis are presented showing the variability of the heating demand and contrast between mid-season and winter.

CASE STUDY

The case study encompasses five tower buildings which are identical in layout, orientation, construction and heating system. These buildings are located in Southampton, UK and were built in the late 60's but retrofitted in the last decade to meet BREEAM excellent certification standards. The towers are classified as social housing composed of 104 flats each (N=520 flats). Given the number of dwellings and the independent connections required, the heating system in each building can be compared to a heat network or small-scale district heating network.

Regarding the architecture, all floors have the same layout with flats distributed along a central corridor. There are two flat (apartment) typologies: one-bedroom flats of 50m^2 and two-bedroom flats of 75m^2. The retrofit involved upgrading the envelope of the buildings resulting in U-Values of 0.30 W/m^{2}K for the external walls and 1.2 W/m^{2}K for the windows.

Besides the improvement in the building fabric, the main upgrade also included the change of the heating system from electric to gas. In the UK, building regulations do not allow the use of gas networks in high-rise buildings (Office of Fair Trading, 2011). Therefore, a high temperature wet heat network was installed supplied by a cascade of four 150kW gas condensing boilers in each tower block (See Figure 1 and Table 1). The network supplies heat for both space heating and hot water to heat exchangers in each flat. Within the flats there are radiators, all equipped with TRVs (Thermostatic Radiator Valves). All flats have an on/off switch, thermostats and timers to regulate their heating and hot water.

Regarding the local climate, according to Köppen and Geiger, the climate in Southampton is classified as Cfb (temperate and oceanic) with an average Heating Degree Days of 1,937. The average yearly maximum and minimum temperatures are of 14.5°C and 8.2°C respectively, and the months with observed largest temperature variability are November to March (Met Office, n.d.).

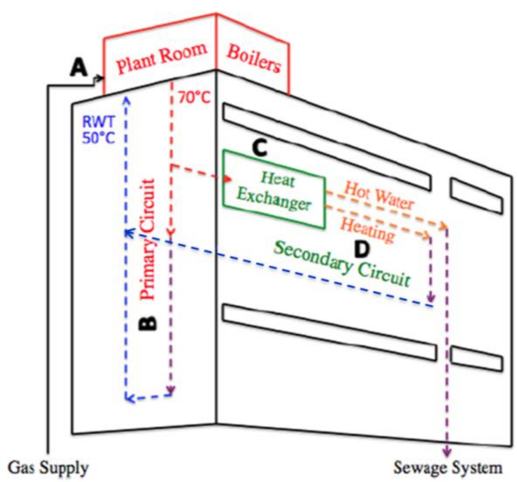

Figure 1 - Heating network in each tower block.

Table 1 - Heating system components in each tower

BOILER	
Quantity	4
Boiler Output (Condensing) Min	32.5 kW
Boiler Output (Condensing) Max	158 kW
Mean Boiler Output (Condensing)	70°C
HEAT EXHANGERS AT FLAT LEVEL	
Heating Capacity	19/31 kW
Return Water Temperature to Primary Circuit	40/55°C

METHODOLOGY

Heating demand records

The data used for this analysis consists of 5,000 anonymized monthly heat meter readings at flat level from each of the five towers covering the period September 2013 to May 2017. These readings include heat used for space heating and hot water. The datasets were firstly examined to identify incomplete readings and errors. Consequently, the readings from September and October 2013 were excluded due to missing data in more than half of the buildings.

Secondly, the distribution of the resulting datasets was evaluated to identify outliers. A maximum limit was set using the top 95th percentile and all negative readings were eliminated from the dataset. Thirdly, as the actual occupancy of the flats was unknown, a minimum value of monthly total heat demand (including space heating and hot water) of 76kWh was defined as a threshold for determining occupancy. Where the total heat demand of a flat was lower than that threshold, the flat was considered empty for the given month. Only occupied flats were used for the subsequent analysis. The new generated datasets without outliers and unoccupied flats were used for the analysis.

Thirdly, the total heat demand in kWh/m^2 was calculated considering the surface area of each flat to normalize the demand across different types of flats. This was then separated into space heating and hot water. Two assumptions were made at flat level: (1) hot water demand is constant through each year for each flat and (2) there is no space heating demand from June to September. The hot water demand was estimated by averaging the heat demand of each flat from June to September. Space heating was obtained from subtracting hot water demand from the total heat demand.

The five resulting datasets of monthly total heat demand, one for each tower, were tested for normality and all were non-normal distributions with a positive skew. Hence a Kruskal Wallis test was used to assess for differences between each towers' dataset. Results indicated a significant difference between the datasets at 0.05 level of significance (H (4) =90.8, p=2.2E-16). Consequently post hoc tests were performed, showing differences only between one tower (tower E in Figure 2) and only some of the others (towers B and C in Figure 2). Given that the results were not conclusive, and that all towers host the same type of demographics, it was chosen to group all the towers together.

The following step was to test for differences in the distributions based on flat orientation. All towers are aligned and given their layout; there are two possible orientations: North West or South East. The results

from a Kruskal Wallis test (H (3) =46.8, p=7.8E-12) showed significant differences across the two orientations, indicating that the datasets should be analyzed separately.
After testing the total heat demand, the same analysis was repeated for both domestic hot water and space heating demand individually. Both datasets showed the same characteristics: no conclusive results when comparing across buildings and significant differences across flats with different orientation. Therefore, the datasets were grouped by flat orientation, and monthly statistics were obtained for domestic hot water and space heating separately.

Weather records

Weather records from October 2013 until May 2017 were obtained from a local weather station (Anon., n.d.). The dataset was formatted to obtain hourly and daily temperature averages. Hourly values were used to calculate heating degree hours considering a base temperature of 15.5°C and summed into monthly totals. Daily temperature statistics were generated to evaluate temperature variability across months.

RESULTS

Hot water

Hot water demand was obtained from the total heat demand as explained in the Methodology section, resulting in a mean monthly demand of 3.0kWh/m^2 for both orientations and annual means as shown in Table 2. As a comparison, a building compliant with UK building regulations is expected to consume 55 kWh/m^2 year of hot water (Pelsmakers, 2012). Variability was not evaluated, as hot water demand was considered constant through a same year for each flat and the main focus of this paper is the analysis of space heating demand.

Table 2 - Domestic hot water demand statistics

Flat orientation	**Mean** (kWh/m^{2}year)	**Median** (kWh/m^{2}year)
North West	36.9	32.7
South East	35.9	33.8

Space heating

First, the distribution of the space heating demand was reviewed. As described in the methodology section, the datasets were first compared across towers to test for differences. Figure 2 shows the profile of the mean monthly space heating demand for each tower, together with the Heating Degree Days for each month. All towers show similar profiles, which follow the one of the HDD.

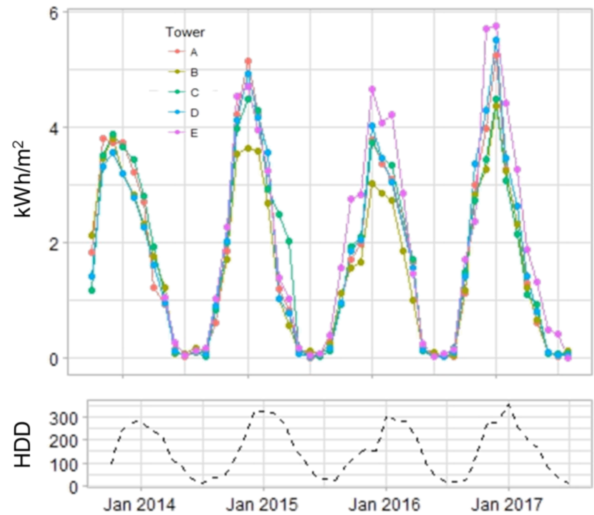

Figure 2- Flat monthly mean space heating demand in kWh/m^2, by tower

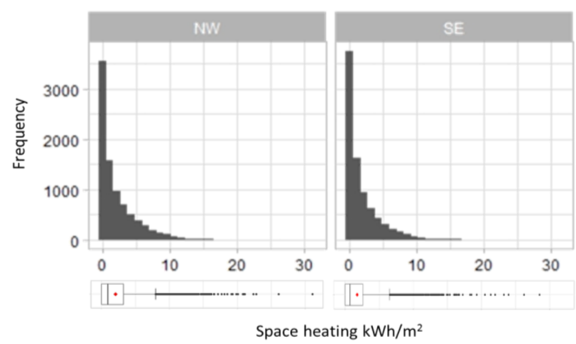

Figure 3- Distribution of flat monthly space heating demand in kWh/m2

Table 3- Space heating demand statistics

Flat orientation	**Mean** (kWh/m^{2}year)	**Median** (kWh/m^{2}year)
North West	23.7	18.1
South East	20.2	14.3

After grouping all towers, the next step was to analyze the demand characteristics by orientation. Figure 3 shows the distributions of the monthly space heating demand in kWh/m^{2}for each orientation; both are positively skewed with means of 2.0 kWh/m^2 for North West flats and 1.7kWh/m^2 for South East ones. Additionally, Table 3 shows the mean and median annual heat demand for each orientation. Considering that the benchmark for space heating in Passivhaus certified buildings is of 15 kWh/m^{2}year for new build and 25 kWh/m^{2}year for retrofits (Pelsmakers, 2012), the heat demand in the towers is very low. However, the values coincide with what expected based on an Energy Performance Assessment performed on one middle flat in one of the towers, which shows an expected demand of 31.6 kWh/m^{2}year for hot water demand and 17.8 kWh/m^{2}year for space heating.

Variability of space heat demand

Figure 4 shows the mean monthly space heating demand across the monitored months and the corresponding interquartile range. This metric was chosen as a measure of the spread of the data, and not standard deviation, given that the space heating demand is non-normally distributed and positively skewed.

Firstly, it can be observed that for both type of flats, North West and South East, the months with higher variability are November to March, with January showing the highest spread in the demand. Secondly, months at the start and end of the heating season showed lower means with minimums of zero, indicating that some users did not use space heating at all. This coincides with the findings from the English housing in the Energy Follow up Survey (Building Research Establishment Ltd (BRE), 2013) where houses showed different seasonal heating patterns. Finally, from June to September, the heating demand was established as zero based on the analysis methodology previously described.

Furthermore Figure 5 shows the daily mean outdoor temperatures across the monitored period and their variability, in the form of the range within each month. Winter months showed the highest variability and

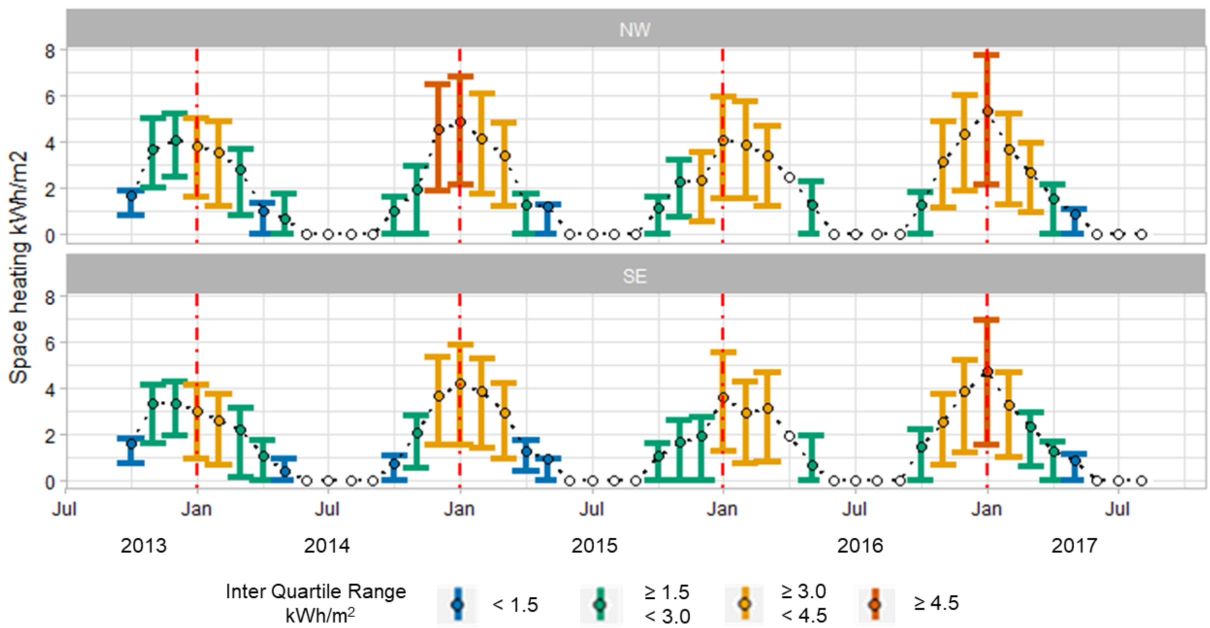

Figure 4 – Flat monthly mean space heating demand in kWh/m^2

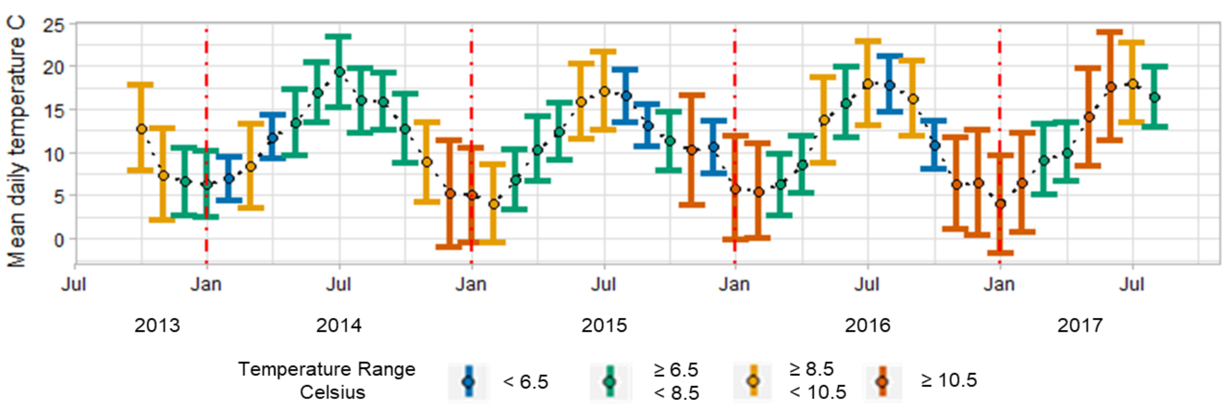

Figure 5- Monthly mean daily temperature (Celsius)

among then January had both high variability in temperature and space heating demand. Interestingly, October to December 2013 had higher heating demand than the following January, yet average daily temperatures were higher.
Moreover, Figure 6 shows the monthly heat demand by Heating Degree Days. This unit allows a direct comparison between months with different temperatures and serves as an indication of the relationship between outdoor temperature and space heating demand in the buildings. Firstly, heating calculations assume a constant ratio of demand by heating degree days across the entire heating season. This was not the case for any year or flat orientation. Most cases showed a bell shaped profile, with highest values in December and January, with the exception of the 2013/2014 heating season.

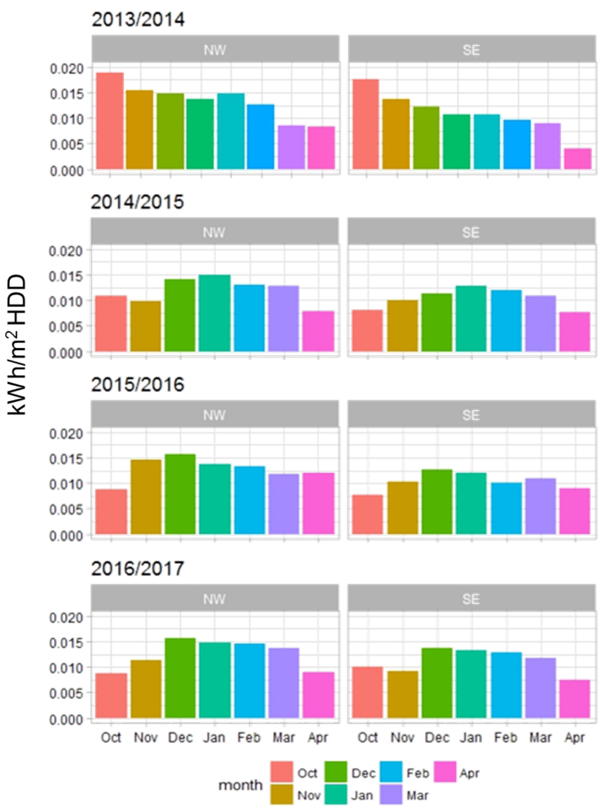

Figure 6 - Comparison of heating demand across months of the heating season in kWh/m2 HDD

Additionally, both November 2013 and December 2015 showed higher or equal levels than the following Januarys and the 2013/2014 season records showed higher levels of heating during autumn months than in winter. The seasons of 2014/2015 and 2016/2017 instead showed higher levels during winter months, and the 2015/2016 showed higher levels in the beginning of the winter.
Finally, the space heating demand had a strong correlation with Heating Degree Days (R^2 of 0.90 for South East flats and 0.91 for North West flats) as shown in Figure 8. The data points further from the line and with higher spread correspond to mid-season months, whereas the data points for January and February are closer.

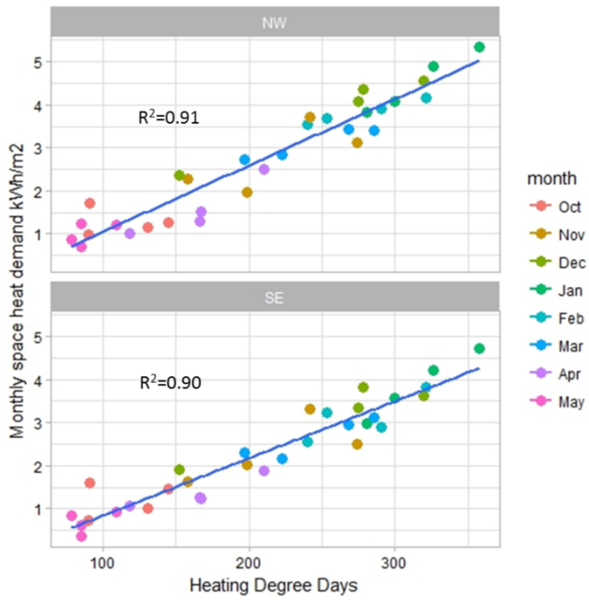

Figure 7 – Relations between heating demand and Heating Degree Days

DISCUSSION

Regarding the building heating demand, records showed low values for both hot water and space heating in comparison with standard values for low energy buildings. This could be attributed to the buildings' thermal performance, as predicted by the Energy Performance Assessment; they are highly insulated, and the architecture consists of a compact layout with almost no possibility of cross flow ventilation. It could also be the case that being social housing, residents are financially constrained and cannot afford to heat their houses. It is necessary to monitor indoor temperatures and occupant's thermal comfort to evaluate whether occupants are underheating their houses or are falling below the fuel poverty line. Finally, the efficiency of the heat distribution network needs to be evaluated. Uninsulated pipes could be generating residual heating in the buildings. The design of a system should consider the impact of residual heating in the heating load.
Furthermore, in contrast to what expected, space heating demand showed the highest variability during January, coinciding with the highest outdoor temperature variability. This could be caused by disparities between demands at flat level; further analysis considering flat characteristics is needed.
Additionally, it is necessary to evaluate the weather variability in more detail, to identify extreme events or sudden changes in temperature. Using running mean temperatures instead of daily averages could

give a better understanding on the variability of the heating demand. This concept could also be taken into practice in the management of heating systems by incorporating weather compensation, which introduces devices that vary the flow temperature of the system based on the outdoor temperature. This is particularly useful in months with high temperature variability (Department for Business, Energy & Industrial Strategy, 2016).

Moreover, to analyze how this variability affects the efficiency of the system and what the peak-load of the system is, higher resolution data is needed. Monthly records are not enough to evaluate the development of the demand, this analyses only provided an overview of demand at flat level. It is possible that flats with different demands offset each other, leading to a uniform heating demand at building level.

Regarding mid-season performance, the variability proved to be higher during the start of the heating seasons than at the end, coinciding with lower temperatures and higher temperature variability as well. Based on the analysis against Heating Degree Days, space heating demand was highly correlated to outdoor temperature.

It is possible that there are other factors to be considered for estimating heat demand in mid-season. Future analysis should be done at a higher granularity and considering flat characteristics such as orientation and occupant behavior profiles. At a day or hourly level, temperature running mean should be included in the analysis given their effect on occupants' thermal comfort (Nicol, 2002).

With regard to the level of heating, the, results show variations across months in contrast to what assumed in calculations. Standards methodologies assume that the heating required per Heating Degree Day is static throughout the year and dependent only of building thermal properties. Figure 6 shows that this was not the case for the towers.

In relation to the analysis developed in this study, several limitations can be identified. The assumption of flat occupancy based on a minimum total heat demand could have introduced error by shifting the distribution of the demand. In addition, space heating was calculated based the assumption that hot water demand was constant throughout the year. However, it could be expected to fluctuate along the year, though not in the same degree as space heating. Finally, the temporal resolution of the data limited the scope of the analysis. Higher resolution would allow analysis of the effect of cold weather events in the heat demand as well as heating patterns.

CONCLUSION

This study presented a preliminary analysis on the heating demand variability of five social housing tower blocks with central heat networks during mid-season months.

Results showed that heating demand in the buildings is very low in comparison to energy benchmarks. Secondly, load variability is high both during winter and mid-season months. Thirdly, the amount of heat required by Heating Degree Days is not constant throughout the entire heating season, as assumed for calculations.

Finally, monthly resolution data is not sufficient to analyze the full impact of the heating load in the efficiency of the heating system. The presented considerations provide pathways to understand temperature variation during mid-season and winter months which will aid optimized designs of heating systems in social housing.

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