

Impacts of fixed-rate charges on heating and controls use in communal network social housing

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Abstract

Winter heating season behaviour in 1960s council tower block flats connected to a heat-network, with fixed-rate charging is presented.

Heating hours delivered to radiators varied between 95 hours (2% heating season) and 4345 (99%) with a mean of 2790 (63%). Over 50% of tenants stated their heating strategy as 'Heating always on and control with TRVs'. Radiator temperature observations confirmed this behaviour. Of people who used timer control, total heating hours reduced with increased frequency of manual intervention.

Mean indoor temperatures up to 27.7°C were observed, implying many residents are adapted to higher indoor temperatures. This is due to current shared cost recovery model which encourages wasteful behaviour. Education on use of controls is key to transitioning residents to charging for actual heat use.

Keywords Adapted thermal comfort, heating behaviour, social housing, communal heating, heating controls.

1. Introduction

The use of district heat-networks and communal heating offers residential housing blocks an efficient solution to meet carbon emissions targets. A significant benefit to using a communal heating system is that an entire building or network can be upgraded to a more fuel-efficient and/or lower-carbon heating solution in one instance. The continued development of heat network technology has seen the gradual reduction in distribution temperatures. This improvement is predicted to continue in the future and will further reduce best-practise network energy losses and resulting carbon emissions (1-3). Therefore, heat networks and communal heating schemes can provide an element of future-proofing to the building or network. The addition of Combined Heat and Power (CHP) as a heat source can further reduce operational costs if the electricity produced can be used on-site (4). The inclusion of CHP requires constant management to ensure an efficient run-strategy and optimal electrical generation is maintained (5).

These benefits make district heat-networks and communal heating an inviting proposition for Local Authority owned social housing, where the provision of an economic and consistent heating supply is essential.

New and existing heat networks and communal heating schemes are required to provide individual heat metering and billing to each paying tenant. However, existing networks are able to continue to operate without individual metering where it is not cost effective and technically feasible to install them (6).

The temperature to which occupants heat their homes can have a significant effect on the amount of energy used within a residential housing block and in-turn, the cost of bills and carbon emissions. Furthermore, living at too low an indoor temperature can be detrimental to an occupants' health, while there is little evidence that living at temperatures greater than 21°C is beneficial to health (7).

The World Health Organisation (WHO) recommendation that healthy and active people heat their homes to 21°C in living rooms and to 18°C in bedrooms and other occupied spaces is widely accepted (8).

However, Public Health England published guidance for over 60-year-olds, low-income families and people living with a disability states that indoor temperatures of at least 18°C should be maintained in the winter, and temperatures "slightly above 18°C" could be good for occupant health. It also states that appropriately dressed occupants under the age of 65 and still active, can heat their homes to "slightly less than 18°C" if it provides a comfortable environment. Rooms in which young infants sleep are instructed to be heated to 16-20°C to prevent sudden infant death syndrome (9).

Previous research conducted by the authors highlighted a scenario where social housing tenants were fuel poor and subsequently living at temperatures below the WHO and Public Health England recommendations. In this instance, the building heating strategy was expensive to run, as heating controls are not fully understood so the system is not operated efficiently (10).

The current indicator for fuel poverty is based on the findings of the Hills Review (11), and shows that a fuel poor household has an annual income of less than half the typical English household, with energy needs are more than 20% higher (12). The government strategy for tackling fuel poverty highlights that in 2012, just 16% of fuel poor households in England were social housing. Most were dwellings were low-income, within the private sector.

The inability to afford enough heat to achieve the WHO or Public Health England recommendations for indoor temperature can also impact on tenant health. Physical impacts, such as high blood pressure, respiratory tract infections, allergies and respiratory conditions can all be increased, in addition to psychological effects such as depression, stress and general low wellbeing (13). Furthermore, doctor diagnosed asthma has been shown to be common in homes with high indoor relative humidity and mould odour (14).

2. Case Study Site

The Case Study site used for this paper is the Buckland community heat-network, Portsmouth, UK.

Portsmouth is situated on the south coast of England. The city is primarily located on Portsea Island, while the city boundary spreads onto the mainland. The climate in Portsmouth is typical of the UK with a Köppen climate type defined as Cfb. This climate is also typical of North-Western Europe and can be found in other areas of the world including North and South America, Australasia and East Asia.

The City of Portsmouth is the 89th largest Local Authority (LA) area out of a total of 326 in England (15), in terms of population, while Portsmouth also has the highest population density in the UK, outside of London, with 5,141 people per square kilometre (16). The average Index of Multiple Deprivation (IMD) score for the LA ranks Portsmouth in the lower quartile of the country at 63rd (17). This score considers employment, income, education and skills training, crime, living environment and more, and thus, overall Portsmouth should be considered one of the more deprived Local Authority areas in England (18).

The Buckland community heat-network is located within the ward of Buckland on Portsea Island. The network was retro-fitted to the site in 2003, before this, each building that is now served by the network had either a building level communal heating system or flat level individual gas boilers.

The heat-network is categorised as an 'Option B2' scheme under Table 5 of the CIBSE Heat Networks: Code of Practice for the UK. It is defined as such as the network is owned by Portsmouth City Council, but operated, managed and maintained by a Private Sector Company (PSCo). Portsmouth City Council are responsible for billing the tenants for heat (19).

The network itself has 3 heat sources, situated in a central energy centre. Heat is generated from 1 CHP unit and 2 gas-fired boilers. The energy centre also has an external, 70,000 litre hot-water storage tank. The electricity generated by the CHP is sold directly to the National Grid, except for the parasitic load of the energy centre. This is because there is no private wire network to allow the electricity to be used within the buildings on the network or surrounding it.

| Energy Source | Output (MW) | Capacity factor |
|------------------------------|-----------------------------|-----------------|
| Jenbacher CHP unit | 0.538 _{thermal} | 0.15 |
| | 0.526 _{electrical} | |
| Danstoker gas-fired boiler 1 | 2.0 _{thermal} | 0.85 |
| Danstoker gas-fired boiler 2 | 2.0 _{thermal} | |

Table 1 – Energy sources installed at the Buckland Heat Network

The network serves 536 flats, within 8 housing blocks. All 8 blocks are owned by Portsmouth City Council and the flats are let to social housing tenants only. The 8 blocks are made up of 4 matching pairs, of varying size and construction type, as shown in Table 2.

| Blocks | Number of Flats | Year of Construction | Construction Method | Estimated External wall U-value (W/m ² K) |
|--|-----------------|----------------------|------------------------------|--|
| Pickwick and Copperfield | 88 each | 1958 | Core Ring Beam | 2.0 |
| Barkis and Nickleby | 136 each | 1965 | REEMA (large concrete panel) | 2.0 |
| Cheeryble and Weller | 17 each | 1962 | Traditional | 0.3 * |
| Blackwood and Brisbane | 26 and 30 | 1954 | Traditional | 0.3 * |
| * These blocks have benefitted from retrofitting blown cavity wall insulation to reduce their external wall u-value from an assumed 1.6 W/m ² .K. | | | | |

Table 2 - Summary of Network Housing Blocks with Construction and Performance

2.1 Existing method of charging for heat

According to Portsmouth City Council, due to the high demand for social housing in the city, tenants are rarely able to specify which housing block they live in. As such, Portsmouth City Council have decided to use a shared cost recovery model at the Buckland heat-network so that tenants aren't penalised for living in less thermally efficient buildings, such as Pickwick as compared to Cheeryble in Table 2. This charging mechanism ensures all tenants pay the same rate for heat in relation to the size of their flat. The tenants do not receive any instruction on how to operate their heating system.

Each year the council calculates the costs of running the network, less the income generated from the sale of the CHP electricity to the National Grid, based on the average of the past 5-years. This 5-year averaging smooths out the effect of a particularly cold winter season, such as 2017/18. The 5-year average cost is divided between each flat, based on the total number of bedrooms and billed with their rent each week. Incorporating this fixed weekly charge into the housing charge also reduces the chance of non-payment by the tenant.

3. Method

This study has conducted space environmental conditions monitoring within 50 occupied flats across the Buckland heat-network. 16 participants were put forward by the scheme managers of the 4 high-rise blocks, these participants were monitored for an initial 2-month pilot-study in February/March 2017 and all were willing to continue participation in the subsequent full study, conducted from September 2017 through until April 2018. The study period of the full monitoring study therefore coincided with the 2017-18 heating season. The additional 34 participating flats volunteered for the study by responding to a letter delivered to all the flats on the network. These flats were monitored for the duration of the full study only.

Two Madgetech data loggers (type RHTemp101A) were placed within the living rooms of each participating flat. These loggers took temperature and relative humidity readings at 5-minute intervals. To determine the radiator temperature, measured as the convected air temperature from within the radiator fins, one logger

was attached, by a cable tie, to the top of the radiator – where possible, out of direct sunlight; while to measure the room air temperature, the second logger was placed on a shelf or bookcase in the same room, away from heat sources and out of direct sunlight.

The same process was replicated in an unoccupied flat over a 3-day period to demonstrate how interactions with the heating system (adjusting the TRV set points) and flat windows affect the radiator and room temperature profiles. These interactions were then used on to base the algorithm status' on.

Of the 50 flats monitored in the full-study, full radiator and living room temperature data was collected from 48, located within 6 of the 8 blocks. It was not possible to recover both radiator and living room temperature data loggers within 2 flats as they were reportedly moved and misplaced during the study period.

The data collection was backed up by face to face interview surveys, conducted at both the beginning and end of the full study to understand self-reported occupancy profile and heating behaviour.

In September 2017, at the beginning of the study period, 48 participants each completed an 'entry' survey. This asked 7 questions, reviewing (i) occupant ages, (ii) approximate hours occupants spent in at home, (iii) an open review of the heating and level of comfort with the home, (iv) estimated target living room temperature throughout the heating season, (v) heating control strategy, including interaction with windows, (vi) what the fixed cost of the heating is and, (vii) whether they deemed the current costs to be fair.

In April 2018, at the end of the study period, 45 participants completed an 'exit' survey. This reviewed the study period in relation to (i) heating system performance, (ii) perceived level of comfort, (iii) heating control strategy and, (iv) overall heat use.

Although the flats connected to the Heat Network are part of a highly maintained Local Authority portfolio, it is important to confirm that the system is operating correctly. Within the exit survey, we asked "Have you had any problems with your heating system or living room radiator this winter?" No participants reported an issue with a TRV. As such, we can assume that all TRVs are operating as expected by the user.

Furthermore, all flats within the data set show radiator temperature profiles that fluctuate whilst heat is delivered to the radiator. As such, we can infer that the TRVs are all able to maintain variable temperatures, and do not suffer from damaged valves, which leave them fully open.

For many flats set points are not consistent. The authors believe this to be indicative of manual intervention with the TRV, not the limiting capacity of the system. There are instances within several flats where a consistent room temperature (staying within +/- 1°C) is maintained, and the radiators are seen to modulate accordingly to maintain this room temperature. During these periods the radiator temperature is lower than the observed maximum, therefore we can infer that the TRV is set below the maximum output. This demonstrates that the TRVs can maintain a fixed room temperature setpoint.

An algorithm has been developed within R, a statistical computing software, to analyse the radiator temperature data and define the radiator status for each reading taken by the data logger. Each readings status is based on a set of conditions which compares the current reading to the value of other readings at given time steps. The set of conditions must be true for the status to be applied to that reading. The reading to which the set conditions are being applied is labelled TS_0 .

The time steps vary in duration and compare the radiator temperature at TS_0 with both future and recent radiator temperatures. Time steps TS_1 and TS_{-1} are 5 minutes after or before TS_0 . Time steps TS_2 and TS_{-2} are 30 minutes after or before TS_0 .

An example the conditions which must be true, in relation to the current time step (TS_0), for the status of “TRV turned up” to be applied are as follows:

1. The radiator temperature at TS_{-2} , TS_0 and TS_2 must all be greater than 30°C (T_{MIN}) and;
2. The radiator temperature change between TS_{-2} and TS_0 must be less than 1°C and;
3. The radiator temperature increase between TS_0 and TS_1 must be greater than 2°C and;
4. The radiator temperature increase between TS_0 and TS_2 must be greater than 4°C .

“TRV turned up” highlights an event where the radiator temperature is increased from a “steady” lower, “on” temperature to a greater temperature, which the also remains “steady”. This change is classified as a manual interaction with the TRV. Where the TRV is “self-regulating” we commonly see the temperature fluctuating between similar peak and low temperatures. This contrasts with a manual interaction where the temperature change is variable. The algorithm ignores the repetitive events and only highlights the single, variable ones.

The algorithm highlights key interactions as (i) each time the TRV setting is adjusted up or down, (ii) each time the radiator is turned on or off, and (iii) determines whether the on/off status is a timer event or a manual event. When compared with a visual interpretation of the code, the heating algorithm achieved a 90.1% agreement.

Figure 1 shows an example 24-hour profile based on the four incident criteria listed above. The heating algorithm read the Radiator Temperature Profile and highlighted the following events:

1. Radiator Turns On – this is a timer event as the heating turns on daily at 03:10
2. TRV turned down
3. TRV turned down
4. Radiator Turned Off – this is a timer event as the heating turns off daily at 22:10

As described above, the 4 low-rise blocks on the network have had the external walls thermally upgraded. this makes the main element of the external building fabric significantly more thermally efficient than the 4 high-rise blocks. Therefore, to allow a uniform comparison of the data and effects, the data collected from flats from within the low-rise blocks were not used within this study. The removal of these flats reduce the participating flat sample to 42.

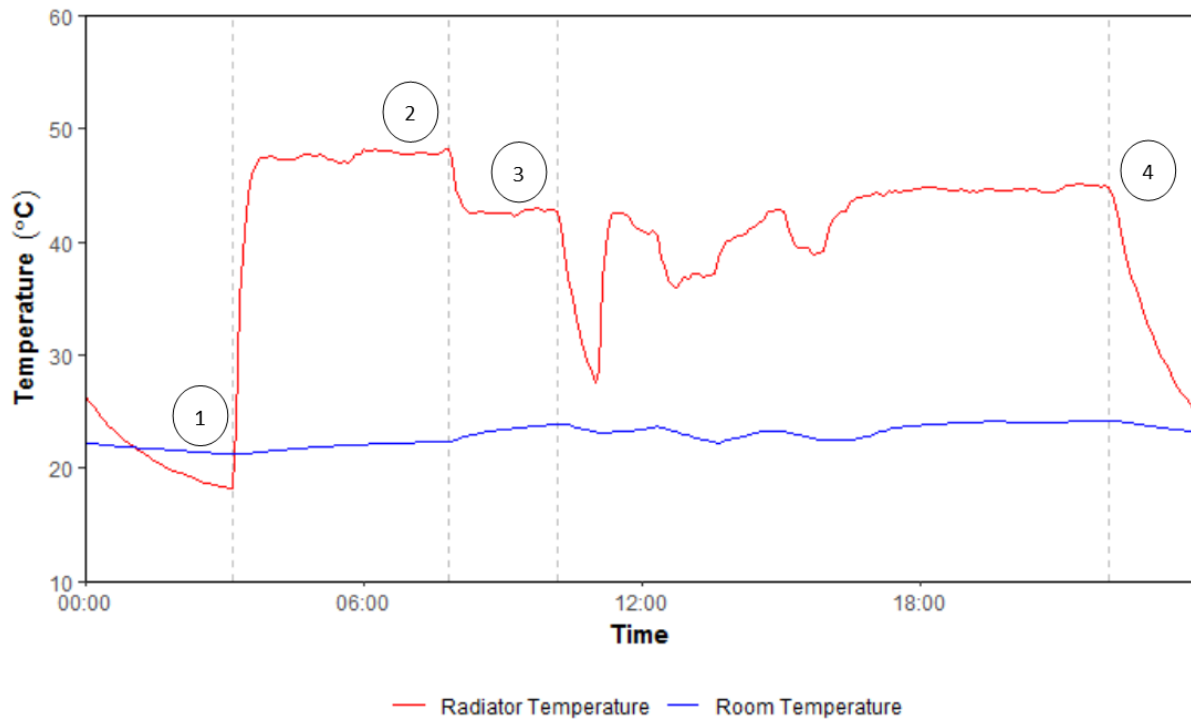


Figure 1 - Example 24-Hour Radiator and Living Room Temperature Profile

4. Discussion

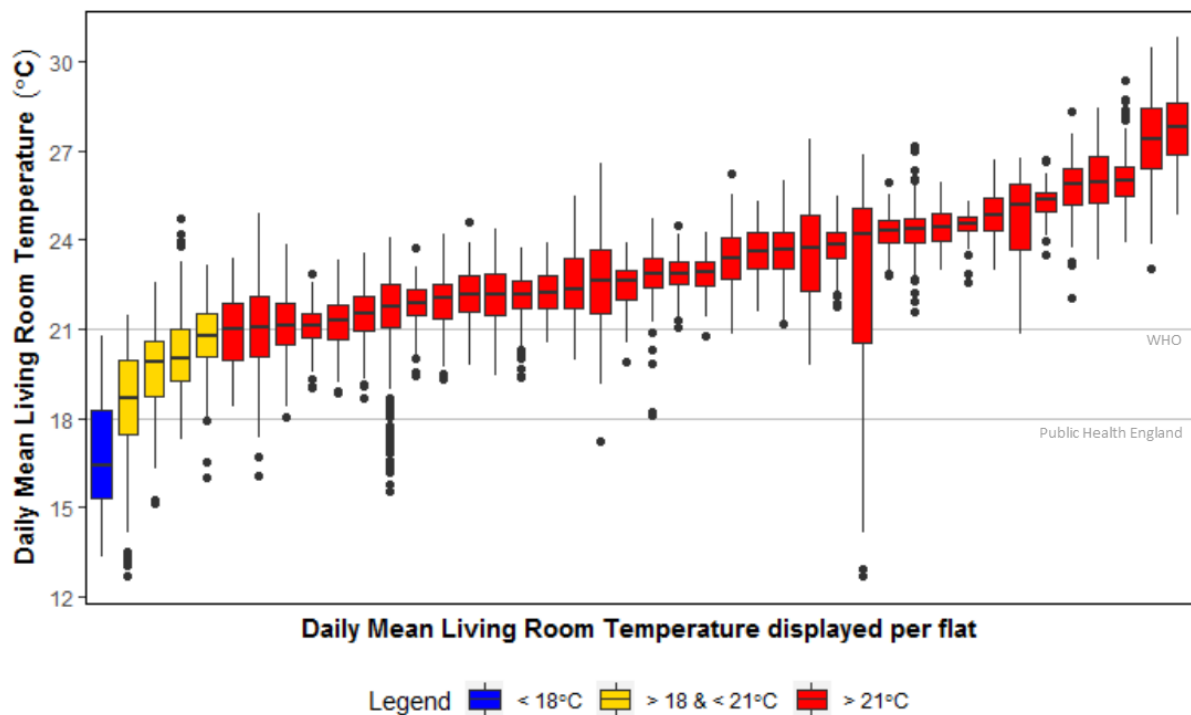


Figure 2 - Daily Mean Living Room Temperature (00:00 – 23:59) by Flat (Oct 2017-Apr 2018)

During the entry survey undertaken at the beginning of the study period, the participants were asked what temperature they know or expect they heat their homes to during the heating season. 17 participants gave values, ranging from 15°C up to

27°C, with a mean expected temperature of 20.6°C. 28 participants said they don't know and 2 chose not to answer the question. This question highlighted that more than half of the residents didn't know what temperature they planned or were likely to heat their home to.

Figure 2, shows the daily mean living room temperature for each of the 42 flats within the 4 high-rise tower blocks. Within the 42 participating flats, overall mean daily living room temperatures were observed from as low as 16.7°C to as high a mean temperature of 27.7°C. The mean temperature observed across the participating flats was 22.8°C.

Only one flat had an overall mean temperature of below 18°C. While the mean temperature of this flat sits below the WHO and Public Health England recommendations, the upper range of the daily means does extend above 20°C. As no residents reported an ongoing or extended duration of heating-system failure via the exit survey undertaken at the end of the study period, it is believed that this indoor temperature is maintained by choice.

Four flats have average living room temperatures that sit between the Public Health England and WHO living room recommendations of 18°C and 21°C respectively. The remaining 37 flats all had a mean living room temperature of greater than 21°C. Furthermore, only 3 of these flats had any single daily mean temperature that dropped below 18°C.

This indicates that that tenants of the Buckland Heat Network are adapted to living at temperatures higher than those recommended as necessary in the UK.

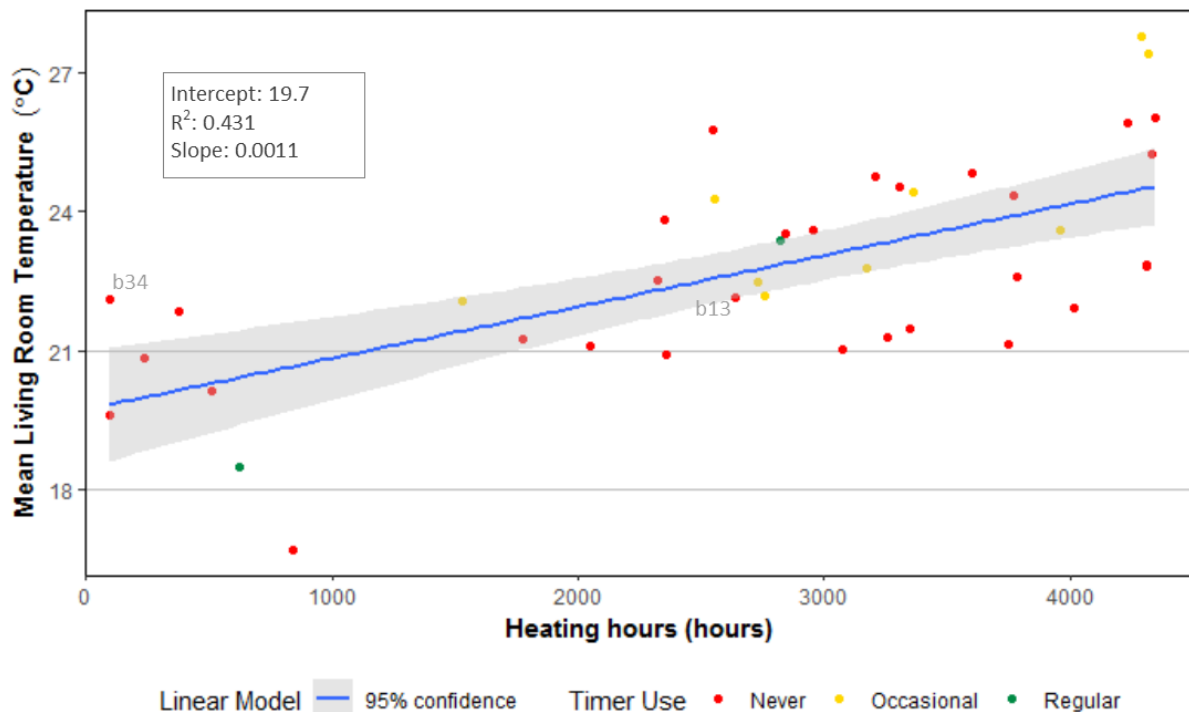


Figure 3 - Mean living room temperature for heating season (00:00 – 23:59) vs Heating hours (Oct 2017 – Apr 2018)

Figure 3 shows a positive correlation between total heating hours and the mean temperature of the living room over the heating season. It is shown that, generally, the more total heating hours, the higher the mean living room temperature observed.

There was a large variability in the heating hours across the dataset, from just 95 hours (2% of the heating season), up to 4345 hours (99% of the heating season). Interestingly, the flat (b34) in which the heating ran for only 95 hours had a mean living room temperature of 22.13°C. In another flat (b13) a mean living room temperature of 22.14°C was achieved but the heating ran for 2639 hours (60% of the heating season). This variation in heating runtime whilst achieving the same mean living room temperature could be due to several factors.

First, Figure 3 does not account for the average radiator temperature, therefore flat b13 may have had its heating on at a low TRV setting for a lot of the time. Alternatively, it could have the heating on at a higher temperature but keep windows open to maintain high ventilation levels. The exact reason cannot be inferred from the radiator temperature data.

However, within the exit survey, participants were asked “which of the following statements best describes how you used your living room windows over the last winter?”

1. I keep them closed in the winter
2. I sometimes open the window for short periods of time (10 mins max), to cool the living room
3. I sometimes (daily, for an hour or two) have a living room window open (to any degree)
4. I almost always have a living room window open to some degree

Flat b13 answered “Statement 4 - I almost always have a living room window open to some degree”, while flat b34 answered “Statement 3 - I sometimes (daily, for an hour or two) have a living room window open (to any degree)”. An increased ventilation rate in flat b13 resulting from “always having a living room window open to some degree” is most likely the reason why heating hours is 2,544 hours higher than flat b34, despite both having near identical mean living room temperatures over the heating season.

Each flat is fitted with a programmer and TRVs. The programmer allows the heating to be set to “On”, “Off”, or “Timer”. The timer is controlled by a dial which allows two heating periods per day to be set. During the entry survey, participants were asked “What do you use to control the heating and temperature of your home?” Figure 4 shows the results of this survey question.

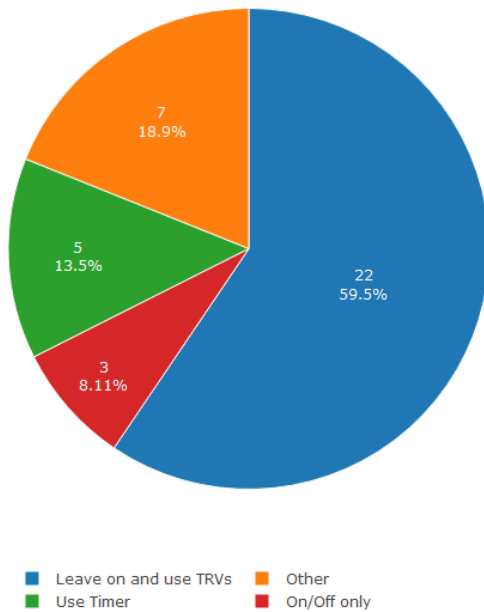


Figure 4 – Tenants’ Self-Reported Heating Control Strategy

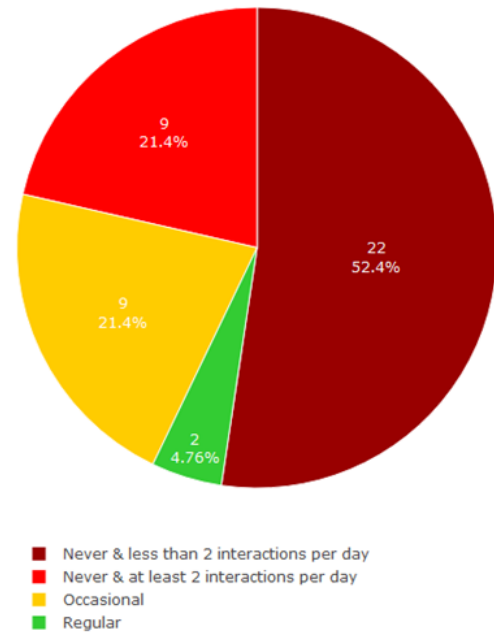


Figure 5 - Participant Inferred Engagement with the Timer Function from Observed Radiator Temperatures

3 participants reported that they only turn the heating on or off at the programmer, and do not engage with the timer function or TRVs on individual radiators. 22 participants (almost 60%) reported that they turn the heat “On” at the programmer and then adjust each radiator using the TRVs. In some instances, it was reported that, once the heating was needed, they would turn the heating on at the programmer and not engage with it again until the end of the heating season. TRVs would be used to turn individual radiators on or off. Only 5 participants reported that they would use the timer function. While the remaining 7 participants reported a variety of other control methods which are included in Table 3.

| Control method response | Number of Responses | Explanation |
|------------------------------|---------------------|--|
| Don't know | 2 | Participants were unsure of how they would control the heating. |
| Thermostat on wall | 1 | Participant reported that they control the heating using the thermostats on the walls. These thermostats were previously connected to the now disused underfloor heating which was used prior to the retrofit of the heat network in 2003. |
| It is automatic | 2 | Participants did not believe that they had to engage with the heating, but that it was an automatic system controlled by the council and would come on as needed. |
| Leave on and use window/door | 2 | Participants would turn the heating on at the programmer and then use the window or balcony door to control the temperature of the room |

Table 3 - "Other" Tenants’ Self-Reported Heating Control Strategies

The observed data, Figure 5, showed that only two participants regularly used their timer, while nine used it occasionally. Overall, a greater number of participants used their timer than said they would in the entry survey. However, in agreement with the entry survey, the data infers that most (31) of the participants never used the timer function. Less than half of these (9) engaged with the heating system, on average, at least twice per day. This means that 22 of the participants did not, on average, turn the heating on and off at least daily over the heating season.

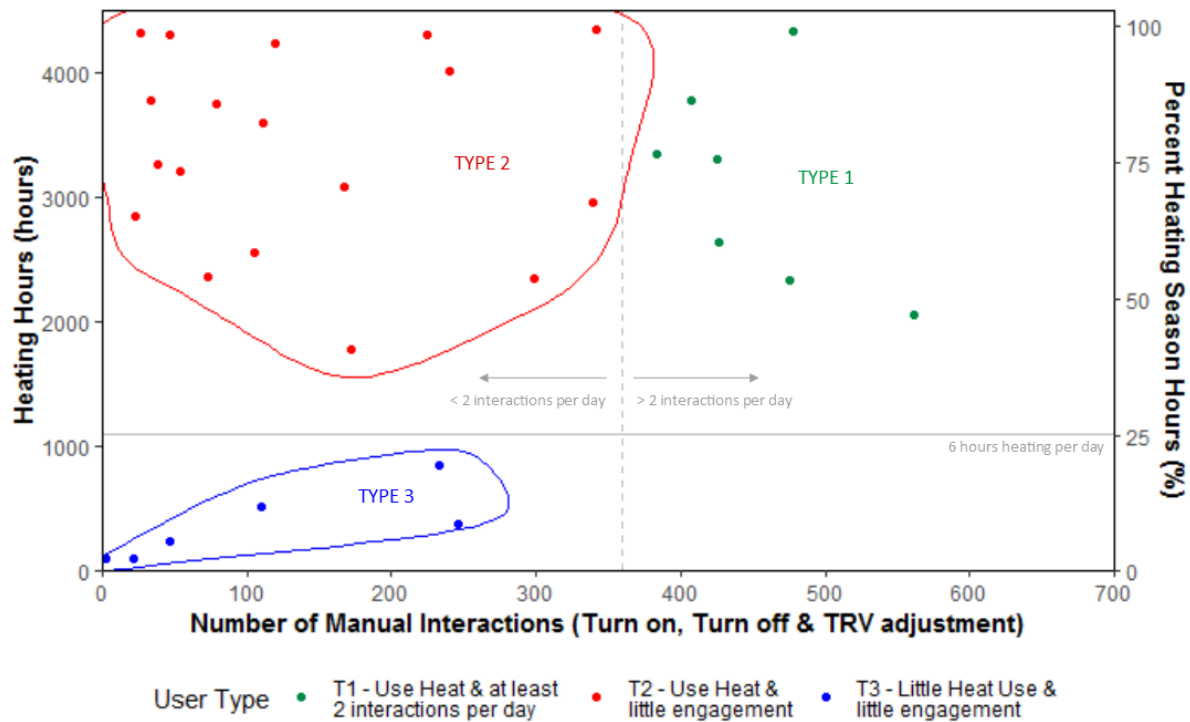


Figure 6 – Heating Hours vs Number of Manual Interactions – Flats that Never Use the Timer (Oct 2017 – Apr 2018)

For the flats who never use the timer, when plotting the heating hours against the number of manual interactions with the heating system (see Figure 6), one can observe 3 types of users.

Type (T)1 use their heating regularly and engage with it at least twice per day. T2 users also use their heating regularly but engage with it less than twice per day. T3 users use their heating less and do not engage with it at least twice per day. The mean living room temperature of each user type is shown in Table 4. In flats that don't use the timer function, there is no apparent correlation between the number of hours heating runs and the number of manual interactions.

| User type | Mean living room temperature (°C) |
|---------------|-----------------------------------|
| No timer – T1 | 23.05 |
| No timer – T2 | 23.17 |
| No timer – T3 | 20.22 |
| Do use timer | 23.40 |

Table 4 - Mean Living Room Temperatures by user type - Flats that Never Use the Timer & Flats that Do Use the timer

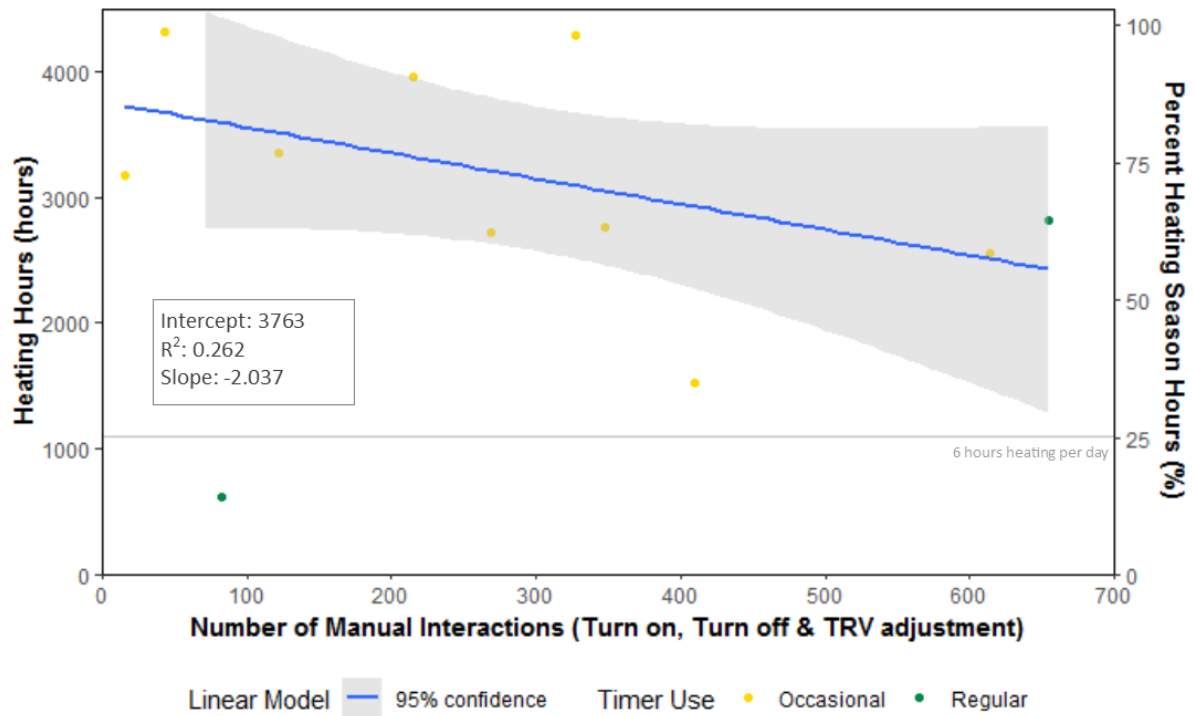


Figure 7 - Heating Hours vs Number of Manual Interactions – Flats that Use the Timer (Oct 2017 – Apr 2018)

The tenants who use the timer function of the programmer demonstrate their ability to use the most complex functionality of the heating controls. This indicates that they may have a better understanding of how to control the heating system than the participants who never use the timer function.

Figure 7 shows heating hours against the number of manual interactions with the heating system for flats who regularly or occasionally use the timer function, and in contrast to Figure 6, there appears to be some correlation.

The linear model, applied to the plot as a line of best fit, shows a modest negative correlation between the two variables through the r-squared value of 0.26. For comparison, an r-squared value of 1 would be a perfect fit of the linear model to the data. The linear model does not include the data point below the “6 hours heating per day” as it is a clear outlier compared to the rest of the dataset. This therefore indicates, that in addition to using the timer function, the more that occupants manually interact with the heating controls, the fewer hours the heating runs. The mean living room temperature of these flats was 23.4°C. This was higher than the mean observed in the 3 user types within the flats that don’t use the timer.

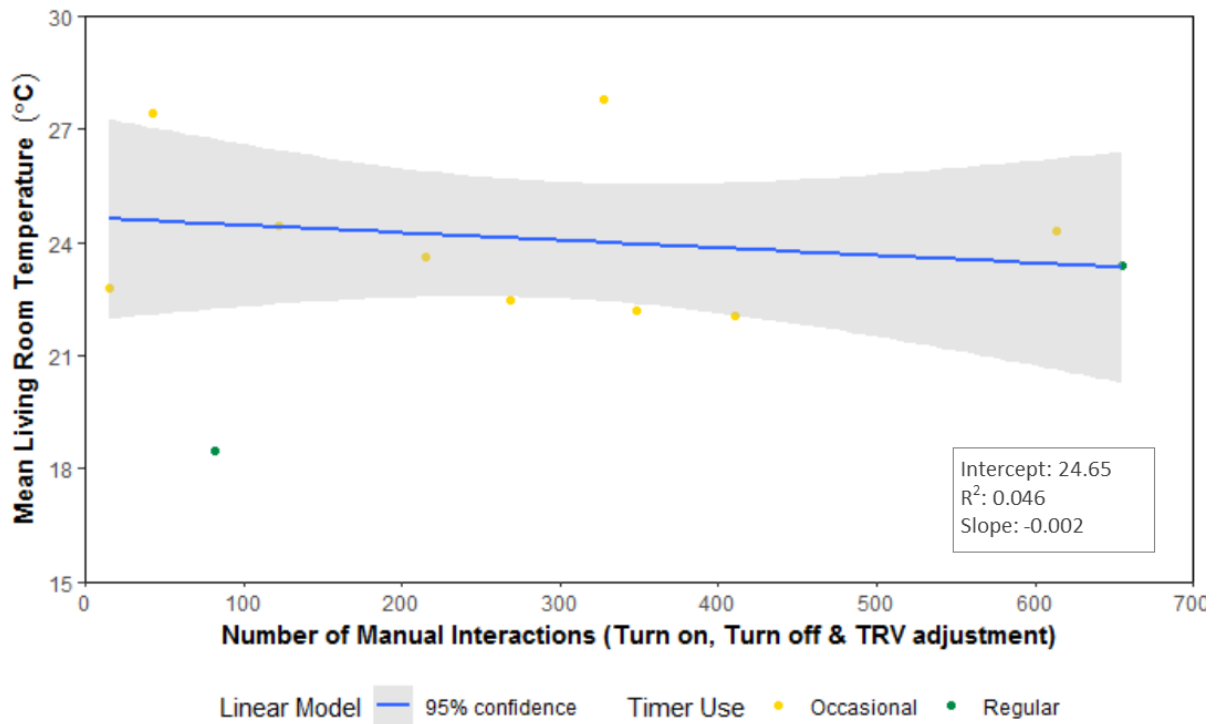


Figure 8 – Mean Living Room Temperature vs Number of Manual Interactions - Flats that Use the Timer (Oct 2017 - Apr 2018)

Figure 8 shows that there is no significant negative correlation between the mean living room temperature and the number of manual interactions with the controls.

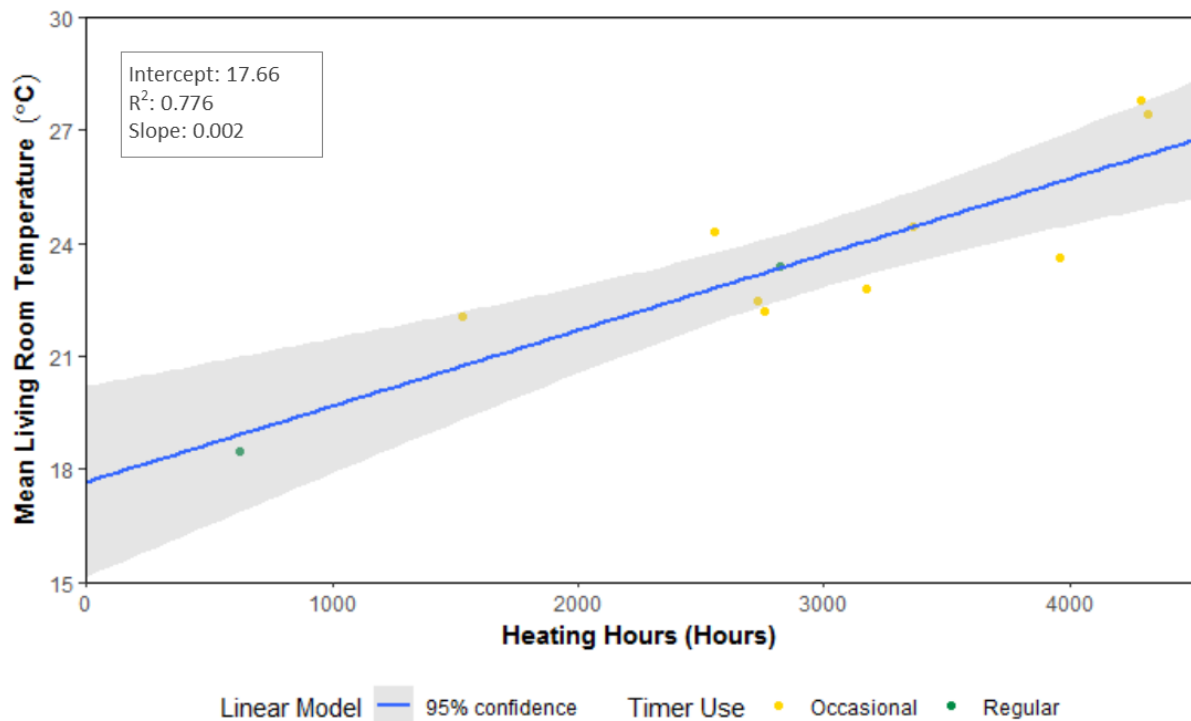


Figure 9 - Mean Living Room Temperature vs Heating Hours - Flats that Use the Timer (Oct 2017 - Apr 2018)

In flats that use the timer function, while there may not be a significant correlation between the number of manual interactions with the controls and the mean living room temperature, Figure 9 shows a moderately strong correlation between the mean living room temperature and heating hours. As such, in flats that use the timer function, if the number of manual interactions with the heating controls is increased, this may lead to a reduction in heating hours over the heating season. A reduction in heating hours should then result in a lower mean living room temperature for that flat.

5. Conclusions

This study has shown that most of the tenants of the Buckland Heat Network are adapted to living at temperatures higher than the self-reported expected temperature of 20.6°C and above the WHO and Public Health England recommendations.

This is potentially precarious for the tenants, who may struggle to adapt to lower internal temperatures or face much higher heating bills if the method of charging for heat were to change or the tenant had move to a dwelling where heat is charged based on individual use.

The primary method of heating control demonstrated within the flats on the heat network is to 'Leave on and adjust TRVs' and among these users, more than half do not interact with the heating system at least twice per day. The observed primary control method is inherent to the current method of charging for heat. Such shared heat cost recovery models allow tenants to use large amounts of heat without any perceived financial penalties, which results in wasteful behaviour. As previously discussed, in practise, the current model is calculated from the average actual network costs over the past 5 years. Therefore, the model would account for a continual increase in heat use across the site and slowly recover the resulting costs from the tenants. Thus, the lack of financial penalty for excessive heat use would be falsely perceived.

This area of Portsmouth is one of the most deprived areas in England in terms of Index of Multiple Deprivation. Yet by charging for heat as a fixed weekly cost as part of the tenants' rental fees, the Council provides heating to over 500 dwellings on the network and consequently none these suffer from fuel poverty.

However, the Council must find a solution to increase tenant engagement with the heating controls and reduce the adapted high indoor temperatures observed, without negatively impacting wellbeing, be that physical or financial.

This paper has clearly demonstrated within Figure 3 and Figure 9, that there is a positive correlation between the mean living room temperature and heating hours. Therefore, a reduction in heating hours across the network, would help to decrease the mean living room temperatures.

Figure 7 showed a modest negative correlation between heating and the number of manual interactions with the heating controls, where interaction is in addition to the use of the timer function on the programmer.

This study therefore recommends:

1. The introduction of a programme to educate all the tenants of the 4 high-rise tower blocks on the Buckland Heat Network to better understand the heating

controls and their operation. It is hoped, that a developed understanding of the heating controls would lead to greater manual engagement, in addition to the use of the timer function.

2. To implement a targeted educational programme to tenants who never use the timer function, phased by the user types highlighted in Figure 6.
 - a. Type 1 tenants would be a good starting point. These tenants showed that, on average, they interact with the heating at least twice per day, and significantly more in some instances. As this group has demonstrated a higher level of engagement with the heating controls already, they may be able to quickly understand and implement the use of the timer function.
 - b. Type 2 users showed little engagement with the heating controls but did use the heating for more hours across the heating season than Type 3. In addition to introducing the use of the timer function, these users may need to be frequently re-educated to encourage greater manual engagement with the heating controls.
 - c. Type 3 users are the least time-sensitive group for education. They currently engage less with the heating, resulting in lower heating hours and interactions with the controls. They have a mean living room temperature of 20.22°C, which is within the WHO guidelines. It is assumed that these tenants choose to live at this temperature so do not require immediate engagement with the education programme.

These findings are intended to inform Portsmouth City Council on how they can successfully encourage a reduction in the high adapted indoor temperatures observed at the Buckland Heat Network, through greater occupant engagement with the heating controls, without negatively impacting on wellbeing. However, these findings may not be unique to this site. Heat networks and communal heating schemes which implement the same type of fixed-rate, shared heat cost recovery model may benefit from a review of indoor temperatures and heating behaviours using the approach outlined in this study.

6. References

1. Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). *Energy* [Internet]. 2014 Apr [cited 2015 Jan 12];68:1–11. Available from: <http://www.sciencedirect.com/science/article/pii/S0360544214002369>
2. Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. *Energy* [Internet]. 2010 Mar [cited 2014 Jul 13];35(3):1381–90. Available from: <http://www.sciencedirect.com/science/article/pii/S036054420900512X>
3. Gadd H, Werner S. Achieving low return temperatures from district heating substations. *Appl Energy* [Internet]. 2014 Dec [cited 2015 Feb 9];136:59–67. Available from: <http://www.sciencedirect.com/science/article/pii/S0306261914009696>
4. Franco A, Bellina F. Methods for optimized design and management of CHP systems for district heating networks (DHN). *Energy Convers Manag* [Internet]. Pergamon; 2018 Sep 15 [cited 2018 Dec 3];172:21–31. Available from: <https://www.sciencedirect.com/science/article/pii/S0196890418307337>
5. Paine S, James P, Bahaj A. Evaluating CHP management and outputs using

- simple operational data. *Int J Low-Carbon Technol* [Internet]. 2018 Mar 12 [cited 2018 Apr 23];1–7. Available from: <https://academic.oup.com/ijlct/advance-article/doi/10.1093/ijlct/cty001/4930757>
6. The Heat Network (Metering and Billing) Regulations 2014. Queen's Printer of Acts of Parliament; [cited 2019 Feb 5]; Available from: <http://www.legislation.gov.uk/uksi/2014/3120/made>
 7. Jevons R, Carmichael C, Crossley A, Bone A. Minimum indoor temperature threshold recommendations for English homes in winter ??? A systematic review. *Public Health*. 2016.
 8. World Health Organisation. Housing, Energy and Thermal Comfort: A review of 10 countries within the WHO European Region [Internet]. Copenhagen; 2007 [cited 2016 Apr 7]. Available from: http://www.euro.who.int/__data/assets/pdf_file/0008/97091/E89887.pdf
 9. Public Health England. Keep Warm Keep Well [Internet]. London; 2015 [cited 2016 Mar 10]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/464858/KWKW_2015.pdf
 10. Dimitriou T, Teli D, James PA., Bahaj A, Ellison L, Waggott A. Impact of current occupant behaviour on potential carbon savings in a council owned tower block undergoing retrofit [Internet]. CIBSE ASHRAE Technical Symposium, Dublin, Ireland, 3-4 April 2014. 2014 [cited 2015 Oct 1]. Available from: http://eprints.soton.ac.uk/364174/1/035_final.pdf
 11. Hills J. Getting the measure of fuel poverty: Final Report of the Fuel Poverty Review [Internet]. London; 2012 [cited 2016 Mar 23]. Available from: <http://eprints.lse.ac.uk/43153/1/CASereport72%28Isero%29.pdf>
 12. DECC. Cutting the cost of keeping warm - a fuel poverty strategy for England [Internet]. London; 2015. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335099/fuel_poverty_consultation.pdf
 13. Maidment CD, Jones CR, Webb TL, Hathway EA, Gilbertson JM. The impact of household energy efficiency measures on health: A meta-analysis. *Energy Policy*. 2014;65.
 14. Norbäck D, Lampa E, Engvall K. Asthma, allergy and eczema among adults in multifamily houses in stockholm (3-HE Study) - Associations with building characteristics, home environment and energy use for heating. *PLoS One*. 2014;9(12).
 15. Office for National Statistics. Populations by Local Authority [Internet]. www.nomisweb.co.uk. 2016 [cited 2016 May 9]. Available from: https://www.nomisweb.co.uk/reports/lmp/la/1946157127/subreports/pop_comp_ared/report.aspx?allInGB=yes&pivot=total&&sort=1&ascending=
 16. Office for National Statistics. Population and Migration: How densely populated is your area? [Internet]. neighbourhood.statistics.gov.uk. 2014 [cited 2016 Dec 6]. Available from: http://www.neighbourhood.statistics.gov.uk/HTMLDocs/dvc134_c/index.html
 17. Department for Communities and Local Government. English indices of deprivation 2015 - File 10: local authority district summaries. London; 2015.
 18. Department for Communities and Local Government. English indices of deprivation 2015 - File 7: all ranks, deciles and scores for the indices of deprivation, and population denominators. London: Department for Communities and Local Government; 2015.
 19. CIBSE, ADE. Heat Networks: Code of Practice for the UK - Raising Standards for Heat Supply. 2015. 1-131 p.

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