Indoor temperatures in UK dwellings: Investigating heating practices using field survey data

by
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Abstract

In 2010 the housing stock was responsible for 30.5% of all energy consumed in the UK. The UK government has set a transition target to reduce the energy used from space heating in dwellings by 29% by 2020 as part of their drive to lower CO_2 emissions and mitigate the risks of global climate change. Housing stock energy models have been developed as research tools to identify pathways to a low energy future. These tools use assumptions about how homes are heated that may reduce their effectiveness at making accurate energy predictions.

This thesis describes the collection and analysis of temperature data from over 300 homes in Leicester to develop better understanding of how dwellings are heated. The temperature measurements were assessed for error and a final sample of 249 dwellings was established. Mean winter temperatures (December – February) were found to be 18.5°C and 17.4°C for living rooms and bedrooms which are comparable with temperatures reported in previous studies. Statistically significant relationships were established between seven descriptors; three technical (house type, house age and wall type) and four social (household size, employment status, age of oldest occupants and tenure). Only 24% of the variation in mean winter temperature could be explained by these descriptors.

Ten heating practice metrics were developed to give insight into how homes are heated; these included the duration of the heating period and the average temperature when heated. Statistically significant relationships were found between the heating practices and a number of technical and social household descriptors. It is concluded that the variation in heating practices which relates to social household descriptors will result in models being unable to make accurate predictions at the regional of city scale. Furthermore, this work has shown flaws in the idealised temperature profile as used in BREDEM. It is suggested that the findings of this work are considered in the development of future stock models.

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1 Introduction

How households use their heating systems impacts on energy use in domestic dwellings. Using temperature data monitored in over 300 dwellings this thesis explores the variation in average indoor temperatures and heating practices in UK homes and discusses the implications of this variation.

1.1 Climate change and energy demand reduction

The scientific evidence in support of anthropogenic climate change is now overwhelming (IPCC, 2007). Climate change is brought about by the build-up of greenhouse gases in the atmosphere. Carbon dioxide (CO_2) is the most significant greenhouse gas due to the quantity that is emitted; predominantly when fossil fuels are burnt for electricity generation, space heating and transport. A reduction in energy use and therefore CO_2 emissions is required to avert the global ramifications of climate change (IPCC, 2007).

Although, the mitigation of climate change is the UK's primary motivation for CO_2 reduction a second motivation to reduce the UK's energy use is to enhance energy security (Costantini et al., 2007). Energy security is defined as the ability to provide a regular supply at an affordable price (International Energy Agency, 2001). As the UK's dependence on overseas energy sources increases so does its vulnerability to future price increases and fuel shortages which could cause problems ranging from the increase of fuel poverty to blackouts.

A third motivation to reduce energy use in the UK is fuel poverty. The report on fuel poverty commissioned by the Secretary of State for Energy and Climate Change argues that fuel poverty is a distinct and serious national problem (Hills, 2012). The report recommends government action to fight fuel poverty which will reduce absolute poverty and diminish the negative health and well-being effects on occupants living in cold homes.

These motivations, to reduce the UK's CO_2 emissions and energy consumption, have led the UK government to set a number of targets. In 2002 the UK government ratified the Kyoto protocol and committed to reducing CO_2 emissions (based on 1990 levels) by 12.5% by 2012. More recently the 2008 Climate Change Act committed the UK government to a legally binding target of 80% reduction of 1990 CO_2 emissions by 2050 (HM Government, 2008). To achieve these targets the UK Low Carbon Transition Plan has defined carbon budgets for each energy sector (HM Government, 2009). As part of these budgets a transition target to reduce the energy used to heat homes by 29% of 2008 levels by 2020 was introduced. In 2011 the coalition Government published the Carbon Plan which outlines the progress to meeting the transition targets (HM Government, 2011).

In 2010 domestic buildings accounted for 30.5% of total UK energy consumption (Office of National Statistics, 2011). This is a significant proportion of total energy use and a major contributor to the UK's overall CO_2 emissions. The domestic housing stock is consequently an area where CO_2 savings are required. There are three options for reducing CO_2 emissions in the domestic sector; [1] Improving energy efficiency of buildings and appliances; [2] Changing behaviour of individuals in households; [3] Decarbonising the energy supply.

Space heating in domestic buildings accounts for 66% of energy used, predominantly through gas fired central heating (DECC, 2011). Hot water heating accounts for approximately 17%, while lights (3%), appliances (12%) and cooking (3%) are responsible for the remainder of the energy used. Space heating is by far the most significant energy end use in dwellings and it consequently it has greatest potential for energy savings; it is therefore the focus of this thesis.

1.2 UK domestic energy reduction policy

The UK government has introduced a number of policies designed to reduce the energy use related to space heating. These include the 'Green Deal' (DECC, 2010) and Carbon Emission Reduction Target (CERT) (DECC, 2011a). The Green Deal was announced in 2010 and makes allowances for householders to borrow money for the purpose of making energy efficiency improvements to their properties. They are then expected make repayments using money saved due to lower energy bills (DECC, 2010). CERT is focused on energy supply companies and requires all suppliers, with more than 50,000 customers, reduce the CO_2 emitted by households by 293 $MtCO_2$ by 2012. CERT necessitates suppliers to make at least 68% of these savings by supplying professionally installed insulation measures. After 2012 CERT will be replaced by a similar scheme called the Energy Company Obligation (ECO) (DECC, 2012). Technical improvements to dwellings such as cavity wall or loft insulation or the installation of energy efficient boilers do not, however, always result in the expected energy savings (Hong et al., 2006). This was evidenced by the Warm Front study, energy use was measured before and after energy efficiency improvements and theoretical energy use compared to actual energy use. It was found that actual energy improvements were approximately 30% less than expected (Hong et al., 2006). This phenomenon is called the ‘rebound effect’ and brings into question the ability of households to make payments based on energy savings (Druckman et al., 2011)(Lowe, 2007). The rebound effect has been used to argue against making efficiency improvements to the existing housing stock (Herring, 2009).

As Green Deal loans are attached to the home and not the occupants it is not possible to guarantee that loan repayments are covered by the energy savings that result from energy efficiency improvements. Energy savings will be predicted using an rdSAP model which currently assumes standard heating practices but will be updated to allow for an occupancy assessment (BRE, 2012). This modelling technique is sensitive to small differences in the heating practices, for example how long heating is used each day and the demand temperature which is set using the room thermostat (Firth et al., 2010). It is essential, therefore, that the occupancy assessment used for the Green Deal is accurate as households that have shorter heating periods and lower demand temperatures than used in the rdSAP model may be worse off financially as a result of Green Deal improvements. This is a potential weakness of the legislation and could cause some households that are most vulnerable to fuel poverty to be worse off financially after energy efficiency improvements have been made to their homes.

A fuller understanding of how occupants heat their homes for the development of future housing stock energy models is required. This need for further research has been echoed in recent reviews of building energy models which suggested that more data is required to validate the findings of energy models and improve the development of new more accurate models (Kavgic et al., 2010)(Natarajan et al., 2011). The Hills review into fuel poverty has also called for more information about how household occupants heat their homes so that the modelling techniques used to produce fuel poverty statistics can be improved (Hills, 2012).

To support the research needs of this area the following questions will be addressed.

1. What are the mean winter temperatures in UK dwellings and how do these relate to social and technical household descriptors?
2. Can mean winter temperatures be estimated by social and technical household descriptors?
3. How can heating practices be estimated using data collected during temperature monitoring studies?
4. How do heating practices vary according to social and technical household descriptors?
5. What are the implications of the findings from the above four questions?

1.3 Aim and objectives

The aim of this work is to identify the determinants of mean winter temperatures (December – February) in UK dwellings and develop a method for the calculation of heating practice metrics which will give insight into how heating systems in dwellings are used. This work will inform the assumptions that are used in building energy models and, consequently, will impact on the development and assessment of UK energy policy.

This aim will be met with the following objectives.

1. Review the academic literature on UK domestic energy use, indoor temperatures in UK dwellings and the methods used to model heating energy use in the UK housing stock. To critically appraise the relevant government policy and show where the literature has identified the impact of heating practices on building energy modelling.

2. Analyse temperature data collected in over 300 homes in the city of Leicester: i) to investigate the relationship between social and technical household descriptors and mean winter temperatures (December – February) in dwellings and; ii) to examine the potential for these social and technical household descriptors to be used to predict average indoor temperatures during winter periods.

3. Develop a methodology for the calculation of a number of heating practices, such as daily heating period and demand temperature, which will give insight into how households use their heating systems and identify how these heating practices vary according to social and technical household descriptors.

4. To document the research to: i) present information regarding heating practices to building energy modellers; ii) draw conclusions regarding heating practices and the variation of mean winter temperatures in UK dwellings; iii) make suggestions regarding the consequences of the variation in heating practices on building energy modelling and UK domestic energy policy; iv) suggest improved methods for the monitoring of indoor temperatures and the measurement of heating practices and; v) make recommendations for further research.

The aim and objectives are documented in the thesis in the following chapters.

Chapter 2. Literature review: Describes domestic space heating and heating practices in detail, discusses building energy modelling and the use of BREDEM-based energy models that prediction of energy use in the UK housing stock and introduces the previous temperature monitoring studies that have been undertaken in the UK.

Chapter 3. Methods – Data collection, processing and analysis: Introduces the data collection, processing and the statistical analysis methods used in the thesis, highlights anomalies and limitations of the temperature data and describes the development of the final sample.

Chapter 4. Indoor temperatures in Leicester homes: Explores the temperature data collected in 249 Leicester dwellings and assesses the potential to predict mean winter temperatures based solely on survey data (Research question 1 and objective 2).

Chapter 5. Heating practices – timing: Introduces 5 heating practice metrics that relate to the timing of heating use in 249 Leicester homes, describes the calculation methods used and shows the variation in each heating practice metric and how the variation is related to social and technical household descriptors (Research question 3 & 4 and objective 3).

Chapter 6. Heating practices – temperature: Introduces a further 5 heating practice metrics that relate to the temperatures which result from heating system usage in 249 Leicester homes, describes the calculation methods used and shows the variation in each heating practice metric and how the variation is related to social and technical household descriptors (Research question 3 & 4 and objective 3).

Chapter 7. Discussion – Implications for domestic energy modelling: Discusses the implications of the findings of the three results chapters and shows how the heating practice assumptions used in BREDEM-based energy models can be informed by this work (Research questions 4 & 5 and objective 4).

Chapter 8. Conclusion: Summarises the main findings of this work, describes the original contribution to knowledge, discusses the limitations of the techniques used and makes recommendations for future research (Objective 4).

2 Literature review

This chapter presents the context for the study of indoor temperature and heating practices in UK dwellings and reviews the relevant academic research and government policy. Section 2.1 describes the UK housing stock and explains how domestic heating systems work. Section 2.2 discusses how what previous research has said about how households and building characteristics influence indoor temperatures and energy use. Section 2.3 introduces building energy modelling with specific reference to how domestic energy models account for heating practices. Section 2.4 introduces the previous temperature monitoring studies. Section 2.5 describes the different heating practices that households use to control indoor temperatures within their homes. Section 2.6 provides an overview of the previous UK based temperature monitoring studies; and Section 2.7 summarises the discussion in the chapter.

2.1 An introduction to domestic space heating

2.1.1 The UK housing stock and domestic space heating

In 2010 the UK domestic housing stock was estimated to comprise of over 27 million dwellings (Communities and Local Government, 2012a). Each year approximately 180,000 dwellings are built (approximately 1% of the housing stock) and very few demolished (ibid). The majority of the existing housing stock will consequently be intact in 2050.

The 2001 Census defines a dwelling as ‘a self-contained unit of accommodation’ and according to national statistics a household is defined as ‘one person or a group of people who have the accommodation as their only or main residence and either share at least one meal a day, or share the living rooms’ (Communities and Local Government, 2012b).

The domestic building stock is complex as it comprises of dwellings that vary in, among other things, size, type of construction, built form (detached, terraced etc.) and year of construction. The composition of the household also varies significantly between dwellings for example, household size, age of occupants, number of children and employment status. Each of these descriptors influences indoor temperatures and energy use in dwellings; this is explored in detail in section 2.5.

In 2010 total UK energy use was 159.1 million tonnes of oil equivalent (toe) (1 toe = 41.868 GJ) (Office of National Statistics, 2011). In 2010 the domestic sector was responsible for 30.5% of total UK energy use and was the second most significant sector after transport (35%) (ONS, 2011). The remainder of the UK energy was consumed by industry (18%), other (including service industries and agriculture) (12%) and non-energy (6%), which includes fuel used for feedstock and oil as lubricant (Figure 2-1).

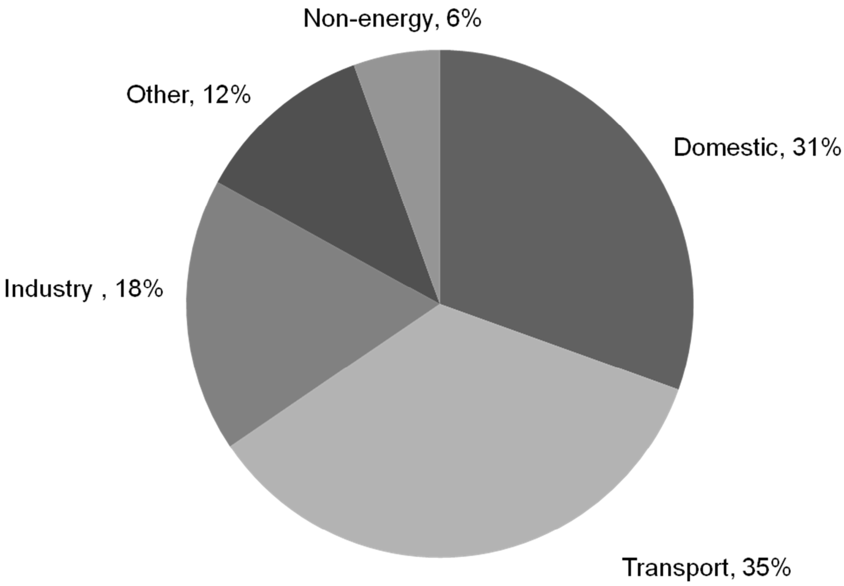


Figure 2-1. UK energy consumption in 2010 by sector (Office of National Statistics, 2011)

In the domestic sector detailed figures for 2010 energy use are yet to be published. The most recent figures are published yearly by the Department of Energy and Climate Change (DECC) in the Housing Fact File (previously titled Domestic Energy Fact File) and are derived using the BREHOMES model. In 2008 66% of energy used in domestic dwellings was related to space heating; a reduction of 10% since 2004 (DECC, 2011) (Figure 2-2). 17% of energy is related to hot water, this is significantly less than published in previous years, as these figures were adapted after a hot water field trial carried out by the Energy Savings Trust found that energy use for hot water was traditionally overestimated (Energy Saving Trust, 2008). The remainder of energy use in domestic dwellings is related to appliances (12%), lighting (3%) and cooking (3%). The energy use relating to space heating is clearly the most significant and will therefore require considerable reduction if government energy and CO_2 reduction targets are to be met. The UK Low Carbon Transition Plan defines a transition target to reduce the CO_2 emissions which relate to space heating in dwellings homes by 29% of 2008 levels by 2020 (HM Government, 2009). Reducing energy used for space heating is therefore a Government priority and consequently this work concentrates on the energy used for space heating in domestic dwellings.

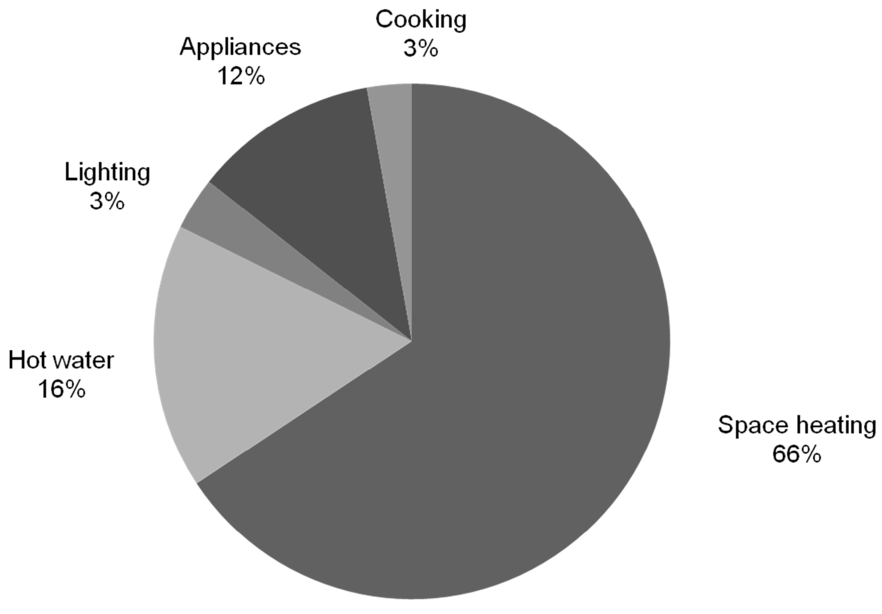


Figure 2-2. 2008 UK domestic energy consumption by end use (DECC, 2011).

Energy use relating to lighting and appliances has increased relatively constantly over the last 40 years but year-on-year does not fluctuate based on outside climatic conditions. The energy used for space heating, however, is influenced by outdoor air temperatures and varies significantly each year as a result. During cold winters more energy is required; this can be observed in Figure 2-3. Despite increases in the thermal efficiency of dwellings, the overall trend between 1970 and 2004 has been an increase in energy used for space heating; this is partially related to the increased number of dwellings in the housing stock but may also relate to households demanding higher indoor temperatures and heating a greater proportion of the dwelling as a result of the increased prevalence of central heating (DECC, 2011). Energy use relating to space heating is complex and published data on the variation of energy use for space heating is based on modelled data therefore more empirical evidence is required about space heating energy use and the heating practices which are used in dwellings.

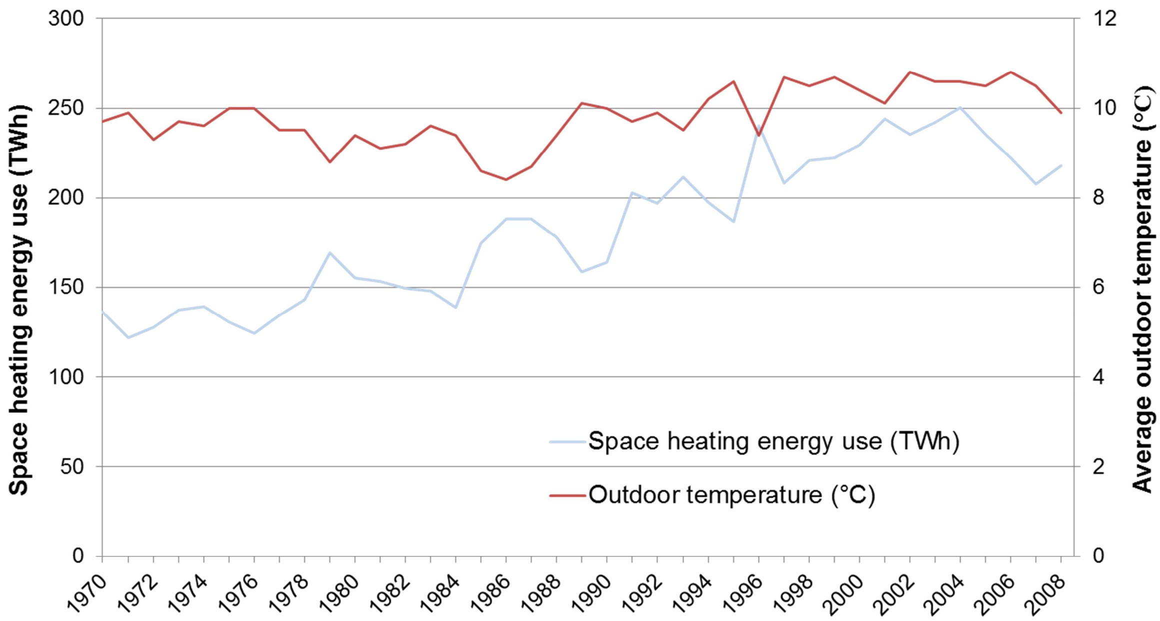


Figure 2-3. Space heating energy use in UK domestic dwellings since 1970 (DECC, 2011).

2.1.2 Central heating systems and controls

Central heating has been installed in approximately 96% of the UK housing stock (DECC, 2011) and is consequently the most common means of controlling indoor temperatures in dwellings.

In a central heating system water is heated by the boiler and then pumped round the dwelling to radiators installed in each room (Figure 2-4). Central heating systems are usually controlled with a timer or programmer which turns the boiler on and off at set times of the day. When turned on the boiler does not constantly heat the water in the system, but cycles, turns on and off, according to the temperature of the water returning (approximately 85℃ depending on the make and model of boiler) to the boiler and the temperature recorded by the room thermostat.

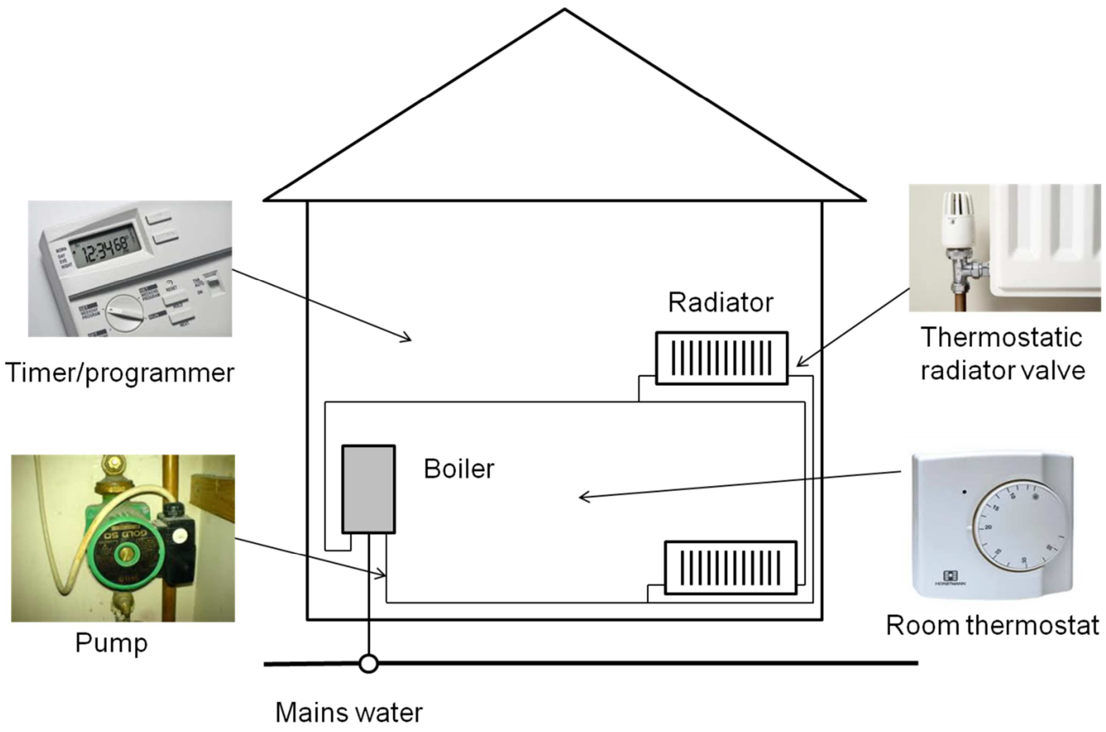


Figure 2-4. Typical components in a central heating system used in a UK dwelling.

Indoor temperatures are controlled by room thermostats and thermostatic radiator valves. During periods when the central heating system is set to be on, room thermostats measure the air temperature and turn the boiler off when the indoor temperature is too high, thus maintaining the indoor temperature which the household occupants have chosen. Thermostatic radiator values can be fitted to radiators in each room (less one which is required to prevent the system being blocked for the pump if all valves are shut down) and allow localised temperature control.

On 1st April 2005 an amendment to the 2002 version of The Building Regulations 2000 Approved Document Part L1 came into effect which stated that the seasonal efficiency of boilers in the UK (SEDBUK) rating should be at least 86% (Office of the Deputy Prime Minister, 2005). This effectively ensured that all new boilers fitted in the UK would be condensing boilers. Approximately 30% of all boilers in dwellings in the UK are now condensing boilers (DECC, 2011).

Condensing boilers achieve high efficiency by pre-heating the cold and or return flow water entering the boiler with the waste heat from flue gases. The increased use of condensing boilers has raised the average efficiency of boilers in the UK from 49% to 77% (DECC, 2011). Monitoring of 60 condensing boilers has been carried out by the Energy Saving Trust (EST); results were reported for 10 regular boilers and 31 condensing boilers monitored for a whole year. The mean efficiency of the standard condensing boilers was 85.3% (standard deviation 2.5%) while the mean efficiency of the combination condensing boilers, which heat hot water on demand as well as heating the water in the central heating loop, was 82.5% (standard deviation 4.0%) (DECC, 2009). Both the standard and the combination boilers were found to have lower in-situ efficiencies than their published SEDBUK efficiencies.

Additional secondary heating is also common in UK dwellings in the form of fixed gas or electric heaters usually in living rooms or portable electric heaters which can be used where required. In 25% of dwellings where secondary heating is present it is rarely used (DECC, 2009). In dwellings with secondary heating, its use has been found to account for 4.1% of the average space heating requirement of the dwelling (ibid).

8% of dwellings, mainly flats, are predominantly heated using electric storage heaters (DECC, 2011a). During periods when electrical energy is cheap (night time) the heaters are used to warm ceramic bricks which act as a heat store. The heat that is stored warms the space via radiation and convection. Storage heaters have become less popular, however, as they provide little control and thus will often be heating the space when it is unoccupied.

2.1.3 Heat loss and energy use in domestic dwellings

During winter periods the indoor temperature in a dwelling is a function of the external air temperature, the delivered heat energy into the dwelling and the heat loss from the dwelling. Heat is lost from a dwelling primarily as a result of thermal transmittance or infiltration. The thermal transmittance (U-value) of the building fabric is the most significant factor that influences the heat loss from a dwelling (CIBSE, 1999). Fabric heat loss is a function of the U-value and the area of building envelope (wall, roof, floor, windows and doors). High heat loss from a building, high U-values or infiltration, will result in low indoor temperatures during unheated winter periods.

Heat is lost from a dwelling in two ways. Fabric heat loss is caused by the transmission of heat through the walls, floor, roof, windows and doors of the building. In steady state conditions the rate of fabric heat loss is given by the following equation.

$$P_t = UA\,\Delta t \qquad \text{Equation 2-1}$$

Where P_t = rate of fabric heat loss (W)

U = U-value ($W/m^2\,K$)

A = area (m^2)

Δt = difference between indoor and outdoor temperature (℃)

The simplest way to reduce the fabric heat loss from a dwelling is to add insulation. This reduces the overall U-value of the building fabric as insulation has a very low U-value and high thermal resistance. For example, a wall that is built from 105mm brick and 100mm dense concrete blocks with a 50mm air space and 13 mm of dense plaster has a U-value of 1.75 W/m^2 K, if the air space is filled with 50 mm UF foam insulation the U-value is reduced to 0.61 W/m^2 K (CIBSE, 1999).

Ventilation heat loss is caused by the loss of warm air and its replacement of cold air from outdoors. In steady state conditions the rate of heat loss via ventilation and infiltration is calculated using the following equation

$$P_v = 0.33\ N\ V\ \Delta t \qquad \text{Equation 2-2}$$

Where P_v = rate of ventilation heat loss (W)

N = rate of air infiltration (number of air changes per hour)

V = volume of the room (m^3)

Δt = difference between indoor and outdoor temperature (℃)

Ventilation heat loss from a dwelling can be improved by installing draft excluders on windows and doors.

The heat loss co-efficient (HLC) is the total heat loss from the building under steady state conditions and is the sum of the fabric and ventilation heat loss components. The heat loss parameter (HLP) (W/m^2 k) is a standardised measure of heat loss given by dividing the heat loss co-efficient by the total floor area and is useful for comparing dwellings of difference sizes.

$$\text{HLC (W/k)} = \text{fabric heat loss } (P_t) + \text{ventilation heat loss } (P_v) \qquad \text{Equation 2-3}$$

$$\text{HLP} = \text{HLC} / \text{A} \qquad \text{Equation 2-4}$$

Where A = total floor area (m^2)

These principles of building physics show that during cold conditions heat loss through the fabric and via ventilation increases and high indoor temperatures will result in greater heat loss and more energy use. A number of dwelling characteristics are related to fabric and ventilation heat loss and therefore influence energy use and indoor temperatures in dwellings. For example, house type is related to the proportion of exposed wall area with detached dwellings having the largest and flats having the smallest. This leads to detached dwellings having greater heat loss than flats and therefore higher energy use when indoor temperatures are the same. During unheated periods high heat loss with result in low indoor temperatures and this will impact on average winter temperatures. As detached dwellings have high heat loss this may lead to occupants who are present during the day having longer heating periods.

2.2 Large-scale survey research

This section introduces the research which has been carried out into the influence of social and technical household descriptors on energy use for space heating and indoor temperatures in domestic dwellings. Despite energy use for space heating being by far the most significant end use of energy in domestic dwellings much of the research into the effects of household and building characteristics on energy consumption have focused on electricity use only. This is partially related to the complexity of monitoring of gas consumption in domestic dwellings (Brown & Wright, 2007).

Research into the impact of technical and social descriptors on domestic energy consumption for space heating falls into three categories, energy modelling, large-scale survey research and temperature monitoring. The three areas are reviewed and insight into the impact of building characteristics and household descriptors on energy use and indoor temperatures in domestic dwellings discussed.

A number of studies which have used self-reported energy use data or billing data from energy companies. These large-scale studies use statistical analysis techniques to identify trends in energy use between dwellings which differ in building characteristics (technical descriptors) of household composition (social descriptors). Few of these however have been undertaken in the UK and therefore there is a gap in the literature and knowledge in this area.

Steemers and Yun (2009) identified the factors that influence energy use in American homes. Survey data was collected from 4822 housing units across 50 states and each variable was investigated using a general linear model. Mean annual energy use for space heating was found to be 14,365 kWh compared to 12,246 kWh in the UK (derived from DECC, 2011). Findings showed that climate is the largest single influence on domestic energy use and occupant behaviour is the second. In the UK climate does not vary as much as it does in the US, due to geographical size, climate will have a much smaller impact and consequently occupant behaviour will be a more significant driver of energy use. It was concluded that building fabric, behaviour of occupants, electrical equipment owned, climate and socio-economic status of the occupants all impact on energy use (ibid). The American housing stock and climate differ significantly to the UK so although some of the trends and relationships found in this work might relate to the UK housing stock it is not possible to know the extent to which they can be applied.

Juodis et al. (2009) surveyed 2280 dwellings in Lithuania and Russia which were part of a district heating scheme and concluded that build quality has a significant impact on heating energy used. Heat consumption calculated for a standard year was reported as being between 153–222 kWh/m^2. The main focus of this work was the variability in heat consumption between identical residential buildings with multiple dwellings and an investigation of the impact of build quality on energy use. It was concluded that real heat consumption differs from predicted consumption but the difference in heat consumption between identical buildings is close to the expected variation that relates to the construction accuracy of the buildings panels. As this study was conducted in buildings supplied by a district heating scheme the heat consumption from individual units within residential buildings was not available and therefore it is not possible to identify any social or behavioural factors which might relate to differences in energy use between similar dwellings.

Guerra-Santin and Itard (2010) aimed to identify the occupant's effect on residential heating consumption in the Netherlands, 7000 surveys were sent out but only 313 were returned and usable, heating practices were found to have a statistically significant relationship with energy use. It was also concluded that the type of heating and ventilation system in the dwelling impacts on occupant behaviour. The very small response rate in this study (only 5%), that was ascribed to the length of the survey, may reduce the significance of the findings, for example, the survey may have been completed by a high proportion of occupants who are retired as they had time to spend completing the survey and therefore the sample may have been skewed.

Vringer et al. (2007) surveyed 2304 households in The Netherlands to discover whether the 'values' held by household occupants impacted on energy used. No discernable relationship was found between the values held by household occupants and their energy consumption, however, a significant difference in the energy use between comparable households was identified. No explanation of the difference in energy use found in comparable households was given.

Meier and Rehdanz (2010) used survey data including space heating expenditure of more than 5000 dwellings in the UK each year between 1991 and 2005, this dataset included over 64,000 observations and was primarily used to investigate the price elasticises which relate to different fuel types. As this work analysed energy expenditures actual energy use was not reported and therefore cannot be compared to other studies. It was concluded that both building characteristics and household descriptors are useful in explaining the variation in energy use across dwellings in the housing stock.

The conclusion is that more detailed data about energy use in the UK housing stock and how it is related to social and technical determinants is required. This will enable policy makers to better target energy efficiency policy. The UK government is rolling out smart meters beginning in 2014 with the aim that they will be installed in all dwellings by 2019 (DECC, 2012a). This will enable significant improvements to the amount and quality of the data related to energy use in the

UK housings stock but will require more understanding of the underlying relationships to be of value.

2.3 Energy modelling research in the domestic sector

Energy models of the UK domestic housing stock have been developed for a number of reasons. These include predicting energy demand in UK dwellings to ensure that supply can be met, understanding which segments of society use more energy which enables policy makers to better target high energy users when designing energy efficiency measures and assessing the potential of energy efficiency policy.

A number of approaches have been taken for the modelling of energy use in the UK housing stock. These broadly fall into two categories; top down models which use national energy and household statistics to show trends in energy use over time and establish the influence of changes in income, climate, energy cost and the social make up of households; and bottom models up which are based on the principles of building physics and are able to quantify specific changes to the domestic building stock such as the impact of a national roof insulation programme.

These two modelling approaches will be introduced and examples of where they inform this work given.

2.3.1 Top-down modelling approaches

The first modelling technique to be addressed is top-down modelling. Top-down models have been developed to inform policy makers regarding the social and economic drivers for energy consumption (O’Neill & Chen, 2002). Top-down models seek to improve understanding of how energy use relates to geographical areas, economic factors, and demographics; how this has changed historically and what impact policy instruments might have on future energy use in different segments of the population.

How households directly influence energy use through heating practices cannot be directly depicted in top down models. Rather, through grouping households into brackets with particular social descriptors (e.g income and age) other attributes of key household members are used as a proxy or indicator of household behaviour. Using this method it is possible to model purchase behaviour for consumer electronics and fuel but not specific energy related behaviour such as thermostat setting.

The most significant UK based top down model is MARKEL which is used as a core policy tool for the UK Government (Kannan et al., 2007) and has been used to establish pathways to the required CO_2 emissions reduction by 2050 (DECC, 2011b).

Additionally, a number of models have been developed for research purposes. In the UK Summerfield et al. (2010) developed two regression models to predict future energy demand. The annual delivered energy and temperature (ADEPT) model uses linear regression on data available since 1970 and the seasonal temperature energy price (STEP) model uses a polynomial regression and is based on quarterly energy data since 1998. Both models were found to have a high level of correlation ($R^2>0.75$) and it was concluded that energy demand is most significantly driven by outdoor air temperature and occupants reaction to energy costs.

Lenzen et al. (2004) utilised an input-output methodology to explore energy use in Sydney, Australia. Australian input-output tables were combined with national data on resource use and pollution and regional household expenditure data. Structural path analysis and multivariate regression analysis was used to establish the relationships between energy use and eight explanatory variables which were; house type, education, household size, population density of the urban area, age, number of children and income. The results show that direct energy use is not increased at higher incomes. Overall income, however, has the strongest correlation to total energy requirement in part due to higher level of goods and services demanded by households with higher incomes.

Druckman and Jackson (2007; 2008) argue that domestic energy use is complex to model and it should take account of a wide variety of technical and lifestyle factors. For this purpose a socio-economic model of the UK Local Area Resource Analysis (LARA) was developed. LARA uses four stages to calculate CO_2 emissions at the national and regional levels; [1] expenditure for fuel is taken from the Expenditure and Food Survey (EFS) which is a survey of approximately 7000 households; [2] household expenditure is converted into energy use using price information for each fuel type; [3] CO_2 emissions are estimated by using emission factors for each fuel; [4] CO_2 emissions are scaled up according to household characteristics which are derived from the 2001 census. LARA uses house type, tenure, age and economic status of the oldest member of the house as a proxy for income. Tenure is used in the model as 21% of registered social landlord properties have more than 15cm of loft insulation, while only 9% of private landlords have this amount (Utley & Shorrock, 2006). This is because although landlords would be responsible for the payment for insulation they are not motivated to make energy efficiency changes as the tenant benefits from lower energy bills.

Predictions made by LARA were compared to energy use data at the national level. The model was then adjusted to fit the national energy use data (Druckman & Jackson, 2007). This was justified as the sample from the EFS was not selected to be nationally representative. Analysis using LARA concluded that households with higher income use more energy. The correlation between income and energy use was stronger for electricity than gas usage.

Morris et al. (2012) use multiple linear regression modelling on UK gas consumption data from lower level super output area (LLSOA) (approximately 500 homes) using a number of data sources. This work was based on 2008 data as this was the most recent year when data was available and aimed to establish the technical and social drivers of gas consumption so that Local Authorities could better target energy efficiency initiatives. 68% of the variation in gas consumption was explained with number of rooms being the most significant descriptor accounting for 52% of the variation alone. House age was not included in this analysis as the data was not available for the whole of England.

Unlike steady-state energy models top-down energy models have the advantage of being able to predict the impacts of economic changes. This makes them a powerful tool for policy makers. They are, however, unable to fully quantify the effect of technical or behavioural interventions.

2.3.2 Bottom-up modelling approaches

Unlike top-down energy models bottom-up energy models can be used to identify the impact of energy efficiency improvements and changes in occupant behaviour in the housing stock.

Steady-state energy modelling tools have focused on technical solutions by analysing heat flows though the built form. Energy models have been used to predict future CO_2 emissions from the housing stock and assess the potential savings related to policy initiatives (Kavgic et al., 2010). Most UK based building stock models of this type are broadly based on the British Research Establishment Domestic Energy Model (BREDEM) which underpins the governments Standard Assessment Procedure (SAP) (Shorrock & Anderson, 1995). A number of versions of BREDEM have been developed including BREDEM-8 which is a monthly version, BREDEM-12 which is an annual version and BREDEM-9 which is a simplified monthly model which forms the basis of the SAP (Kavgic et al., 2010).

BREDEM uses algorithms based on building physics and empirical data to calculate domestic energy consumption by four end-use categories; space heating, hot water consumption, cooking and lights and appliances. A number of building energy stock models have been developed for research purposes and use the BREDEM algorithms to predict the energy use of the housing stock. These include BREHOMES (Shorrock & Dunster, 1997), the Johnson model (Johnston et al., 2005), the UK domestic carbon model (UKDCM) (Boardman, 2007), deCARB (Natarajan & Levermore, 2007), the Energy and Environmental Protection model (EEP) (Jones et al., 2007), the Community Domestic Energy Model (CDEM) (Firth & Lomas, 2009: Firth et al., 2010), the Domestic Energy and Carbon Model (DECM) (Cheng & Steemers, 2011) and The Cambridge Housing Model (DECC, 2012b).

These models vary mainly in the number of building archetypes which they use to model the housing stock; ranging significantly, from the Johnson model which uses only two notional house types to UKDCM which uses over 20,000 dwelling types. As the housing stock is complex and models are designed to predict energy use or CO_2 emissions with limited information assumptions are required, however, many archetypes are used.

The Standard Assessment Procedure (SAP), based on BREDEM-9, is the Department of Energy and Climate Change's methodology for comparing the energy performance of dwellings. SAP and a reduced dataset version of SAP (rd-SAP) are used to produce energy performance certificates of dwellings. The energy and resulting cost savings from energy efficiency improvements relating to the Green Deal will be calculated using rd-SAP (DECC, 2010). Research into the effectiveness of the use SAP based models to make predictions of the energy used before and after refurbishments have questioned its ability to make accurate prediction and have recommended that future development of SAP can account for variation in occupant behaviour (Hong et al., 2006)(Wetherell & Hawkes, 2011). The limitation of SAP to predict accurate energy savings that relate to building retrofit is further exacerbated as SAP uses standard climate data as it does not take location into account.

2.3.3 The use of heating practices in energy modelling

Models based on BREDEM tend to assume standardised behaviour with simplified schedules for occupancy and heating. BREDEM uses an idealised temperature profile as shown in Figure 2-5, h_1 and h_2 indicate the two heating periods (Anderson et al., 2002). The temperature starts at the background temperature which is the temperature when no heating is used. At the point when heating is turned on the indoor temperature reaches the demand temperature instantly and is then maintained constantly until the end of the heating period. After the heating period the indoor temperature decreases until the heating is turned on again or the background temperature is reached.

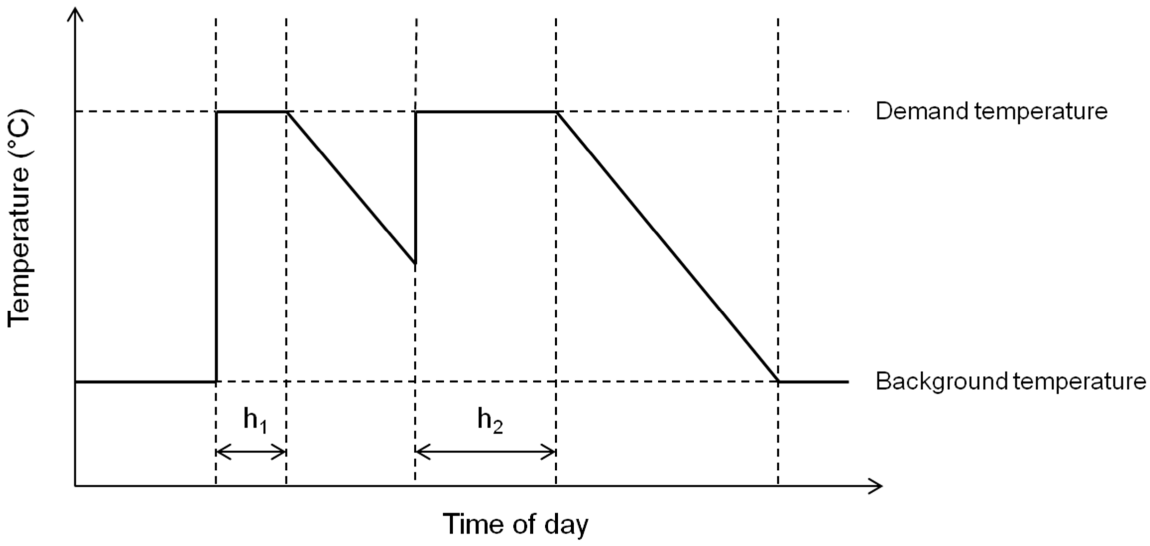


Figure 2-5. Idealised temperature profile used in BREDEM-based models (Anderson et al., 2002).

The literature on BREDEM specifies a thermostat setting of 21°C and a heating period of 9 hours per day (Anderson et al., 2002). These heating practices are provided as a guide and model developers are invited to use their own inputs. DECM, however, is the only UK based stock model which changes behaviour between dwellings, this is done by varying the heating schedule based on the employment status of the household occupants (Cheng & Steemers, 2011). These heating practices together with internal gains, solar gains and other calculations are used in the model to derive average monthly temperatures which are used as the basis for the heat loss calculations.

The impact of the behavioural assumptions in housing stock energy models have been highlighted using parametric sensitivity analysis which showed that thermostat setting (the temperature to which household occupants heat their homes) and heating period (the average daily time period where heating is used) are the most significant inputs into the model (Firth et al., 2010). This finding has been explored further by Cheng and Steemers (Cheng & Steemers, 2011) who conclude that a variation of 2.5°C in indoor temper ature can increase the uncertainly of estimations of CO_2 emissions by 23%. To ensure that future energy consumption predictions from the housing stock are accurate more information is required about how indoor temperatures are distributed across the housing stock.

Currently models are able to predict energy use at the national level but it is unclear whether they are as accurate when predicting energy use in different segments of the housing stock. Natarajan has called for future data sets to be incorporated in stock models (Natarajan et al., 2011). This information will allow modellers to validate the indoor temperatures calculated by stock models and consequently improve the accuracy of energy predictions (Cheng & Steemers, 2011). This work will provide one such data set and addresses the variation in heating practices throughout the housing stock which will enable modellers to predict energy use in different segments of the housing stock more accurately.

2.3.4 Validation of domestic energy models

Most current stock models are validated against energy use data published at the national level. Models can be shown to predict total energy used relatively accurately. Testing models against national energy data, however, has a number of drawbacks and limitations.

1. Government statistics categorise users by how much gas they consume. Consumption of above 73,200 kWh is categorised as commercial or industrial. Below 73,000 kWh is categorised as domestic, however this includes both domestic and small business (ONS, 2009). Consequently, the figures are higher than they would be if only dwellings were included.
2. Some of the national statistics are modelled not measured. Therefore, final consumption figures include a substantial amount of estimated data (ONS, 2009).
3. Regional gas use data is corrected for weather conditions (DTI, 2002). There is a lack of transparency in the documentation and it is difficult to distinguish the figures which are modelled and estimated from those that have a higher degree of accuracy.
4. Stock models are often designed to predict future energy use or the effectiveness of interventions. However, models that predict energy use correctly may not be able to predict accurately for particular interventions if certain assumptions are inaccurate. For example, the total energy used

may be correct, but if heat loss through the wall is overestimated and hot water usage (as has been the case in most models according to the EST) is underestimated any predictions based on interventions to improve built form or reduce how water use will be inaccurate.

5. If energy predictions made by models do not match national energy use data models are ‘fine-tuned’. For example, BREHOMES model has turned up the indoor temperature as the model was found to under predict energy use; however, there is not currently enough empirical evidence to show that this was justified (Shorrock and Dunster, 1997).
6. Energy models validated at the national level cannot be applied at the regional or city scales unless those areas are representative of the national scale both in relation to the housing stock but also the social make-up of the households.

The heating practice assumptions in BREDEM may lead to the prediction of the correct average indoor temperatures but this does not validate their use. If the duration of daily heating periods is underestimated and the demand temperature overestimated interventions which impact of these elements will lead to inaccurate predictions. Additionally, if there is significant variation in indoor temperatures and heating practices related to social descriptors future this should be accounted for in future model developments. Further research is required to establish how heating practices vary across the housing stock and if there are any relationships between heating practices and technical and social household descriptors to inform the assumptions that are used in housing stock energy models.

2.4 Temperature monitoring studies

The temperature monitoring studies based on the UK housing stock have predominantly focused on winter temperatures as energy used for space heating is so significant. A number of studies have presented work on summertime temperatures these include; Indoor temperatures during the 2003 heat wave were measured in five London homes and four homes around Manchester (Wright et al., 2005); Living room and bedroom temperatures were recorded at 45 minutely intervals for 224 dwellings from 22nd July to 31st August 2007 (Firth & Wright, 2008); Overheating standards have been assessed based on temperature measurements during July and August 2009 in 282 dwellings in Leicester (Lomas & Kane, 2012). These studies are beyond the scope of this work which aims to understand how dwellings are heated but can provide important insight into the methods required for temperature monitoring data collection and analysis.

There have been a number of temperature monitoring studies in other counties; of these the one which is most relevant to this work was undertaken in New Zealand (French et al., 2007). Temperature was monitored in over 400 dwellings in living room and bedroom spaces. Temperatures were logged every 10 minutes for a period of a year. It was concluded that living rooms heated by solid fuel were the warmest, however, only 5% of the sample were heated by central heating and consequently results cannot be compared with temperatures measured in the UK.

The first large-scale field study of indoor temperature in UK dwellings was undertaken by Hunt and Gidman (1982). Spot measurement of temperatures in 1000 dwellings were taken during February and March 1978, when it was expected that outdoor temperatures would be close to average for the heating season. Average living room and bedroom temperatures were 18.3℃ and 15.2℃ respectively. These temperatures are lower than those reported in more recent studies which may be related to the increased prevalence of central heating since this study was carried out. The spot measurement strategy used in this study enabled a large sample but does increase the error as temperatures measured over a longer period can be averaged to reduce the impact on short term temperature changes relating to heat gains or losses caused by, for example, solar radiation or window opening. Using spot measurements it is also not possible to know whether the temperature recorded is typical of the dwelling. The determinants of indoor temperature were tested but Hunt concluded that much of the temperature difference between groups such as in the tenure and house age categories were a result of different levels of uptake of central heating. Approximately 50% of the sample had central heating this compares to over 90%

in the more recent studies and consequently makes meaningful comparison difficult.

Table 2-1. Recent temperature monitoring studies in UK dwellings

	Measurement period	Number of rooms monitored	Average temperature (℃)	
			Living room	Bedroom
Hunt & Gidman (1982) (n=1000)	Spot measurement	All	18.3	15.2[a]
Oreszczyn et al. (2006) (n = 1604)	2-4 weeks	2	19.1[b]	17.1[b]
Summerfield et al. (2007) (n = 14)	2 years[c]	14	20.1[d]	19.3[d]
Yohanis & Mondol (2010) (n = 25)	1 year	4	19.4	18.4
Shipworth et al. (2010) (n= 358)	7 months	2	-	-
Kelly et al. (2013)	7 months	2	19.6[e]	-

[a] Mean temperature of the warmest bedroom
[b] Standardised for 5℃ external temperature i.e. winte r temperature – living room temperature relates to daytime (08:00-20:00) and bedroom temperature night time (20:00-08:00)
[c] Reported figures only for one year 2005-6 monitoring period
[d] Standardised for 5℃ external temperature i.e. dail y winter temperature
e Average of all measured living room and bedroom temperatures

The most comprehensive recent study of indoor temperature in UK dwellings was undertaken by Oreszczyn et al. (2006). Temperature was monitored for a period of two to four weeks in over 1600 low income dwellings and the determinants of indoor temperatures assessed. As temperature was monitored in different parts of the country and at different times of the year outdoor air temperature during the monitoring period was different for each dwelling, therefore a standardisation process was required so that temperatures could be compared. Average living room (for daytime periods between 8:00am and 8:00pm) and bedroom temperatures (for night time periods between 8:00pm and 8:00am), standardised to an outdoor temperature of 5℃, were reported to be 19.1℃ and 17.1℃ respectively (Oreszczyn et al., 2006). This study was solely based on low income household so the results cannot be extrapolated to the whole housing stock.

Summerfield (2007) monitored indoor temperatures in 14 UK dwellings built to high thermal standards and found that at outdoor temperatures of 5℃ average living room temperature was 20.1℃. Two monitoring periods were carried out 15 years apart in 1990 and 2005, temperatures were standardised to an outside temperature of 5℃ so that the two periods could be compared, it was found that living room temperatures were slightly warmer than in 2005 but bedroom temperatures were lower than in 1990. This study was undertaken in dwellings which were built to high thermal standards and are consequently not representative of the housing stock as a whole.

Shipworth et al. (2010) measured temperature in over 300 dwellings across the UK. Estimated thermostat setting was derived using an average of daily peak temperature and was estimated to be 21.1℃ (Shipworth et al., 2010). This finding, however, can be influenced by periods of high internal or solar heat gain and it is not possible to ascertain whether the peak temperatures reached is a result of the use of heating systems by occupants to maintain desired indoor temperatures. Average temperatures were not reported and therefore it is not possible to compare the temperatures measured in this study with the other studies that have measured temperature in UK dwellings.

The same data set studied by Shipworth et al. (2010) was used to predict indoor temperatures in English homes using panel methods. The model used to predict average daily temperatures using both technical and social household descriptors and it was able to predict temperatures within 0.71℃ at 95% confidence and explain 45% of the variation in indoor temperatures. The mean daily indoor temperature (calculated from both living room and bedroom temperatures) was 19.6℃ at an average daily outdoor temperature of 9.71℃. The average temperature reported is based on temperatures monitored during the period 1st August 2007 and 31st January 2008, however, the aim of the model is that indoor temperatures can be predicted in different homes according to variation in external climate conditions. The number of occupants, household income and occupant age were found to be important drivers of changes in indoor temperature. House type, construction age and the thermal efficiency of the building fabric were also important model inputs.

Yohanis and Mondol (2010) (Yohanis & Mondol 2010) measured indoor temperature in 25 dwellings in Northern Ireland and reported a living room temperature averaged over a whole year of 19.4℃. The temperatures reported in these papers are not, however, adequate to inform the modelling community as the variation of average temperatures between dwellings has not be shown in a sample which is representative of the housing stock.

Although, the previous temperature monitoring studies have provided valuable insight into the indoor temperatures in the UK housing stock none have provided detailed insight into the heating practices that household occupants use to heat their home and the extent to which the heating practices vary according to social and technical descriptors. Additionally, the determinants of average indoor temperatures have only been explored in a sample of low income dwellings, it is suggested that this work should be repeated on a sample which has not controlled for household income.

Average temperatures and heating practices based on empirical evidence will validate behavioural assumptions used in domestic energy stock models and if average temperatures can be linked to technical or social determinants such as house type or the number of household occupants this will give modellers valuable information which will improve the accuracy of energy predictions.

2.5 The technical and social household descriptors and their expected influence on energy use and indoor temperatures

Based on building physics and the previous research into energy use and indoor temperature this section discusses the influence of technical and social household descriptors on energy use and indoor temperatures during winter periods in domestic dwellings.

2.5.1 Technical descriptors

Technical descriptors are those which describe the building characteristics such as the size or age of the dwelling. There are numerous technical descriptors, however only those which have been discussed in previous research, or those which are discussed later, are introduced here. Five descriptors are described in terms of how they are expected to influence energy use and indoor temperature.

1) House type is the term used to describe the built form of a dwelling. Examples of house type are detached which shares no walls with other dwellings and mid-terrace which has shares two walls. House type is related to indoor temperature as the different built forms vary in the proportion of exposed wall area which they have. Greater exposed wall area will lead to more heat loss thought the building fabric and will therefore lead to cooler indoor temperatures during unheated periods. Detached dwellings do not share walls with other properties and have the highest proportion of exposed wall area. Conversely, flats share walls and floors with other dwellings and have the lowest proportion of exposed wall area. It is consequently expected that on average detached dwellings will have the lowest indoor air temperatures than the other house types and that flats will have the highest. Survey research has confirmed that space heating expenditure is greatest for detached dwellings and least for flats (Meier & Rehdanz, 2010) and that energy use is related to house type (Steemers & Yun, 2009). Multiple regression has shown that the proportion of terraced dwellings in a LLSOA was correlated with gas consumption (Morris et al., 2012). Temperature monitoring research reported contradicting results relating to house type; Hunt and Gidman (1982) found that living rooms in detached dwellings were warmer than other house types while converted flats were the coolest, this result may be related to the high proportion of dwellings which did not have central heating, this is evidenced by French et al. (2007) who found that dwellings heated by solid fuel were the warmest. More recent temperature monitoring also suggested that detached dwellings might not be the coldest house type; Oreszczyn et al. (2006) found that ‘other’ flats were the coldest house type, which is also contrary to expectations; purpose built flats, however, were the warmest house type. Although, energy use related to house type is straightforward how house type is related to indoor temperature seems more complex and suggests that more research is required in this area.

2) House size or floor area relates to energy use as larger dwellings required more energy to increase indoor temperatures to occupant expectations

(Lenzen et al., 2004). Multiple regression analysis has shown that number of rooms can explain 52% of the variation in gas consumption at the lower super output area level (approximately 500 homes) (Morris et al., 2012). Floor area, however, is also related to house type, with detached dwellings generally having the largest floor area (Steemers & Yun, 2009). This makes analysis of the impact of house type more complicated and suggests that larger samples are required so that floor area can be controlled for so that impact of house type can be studied in isolation.

3) House age is related to indoor temperature as changes in building standards and techniques have influenced both the heat loss and the infiltration through the building fabric. As building techniques and standards have improved the average U-value has decreased and building fabric has become more air tight. Newer buildings with low U-values and infiltration will have lower heat loss and are expected to have high indoor air temperatures. Survey research has shown that house age is related to energy use (Steemers & Yun, 2009), however, this result may not be transferable to the UK housing stock as it is related to the fact that newer dwellings built in the US have more built in heating systems and the older houses which are manually controlled and more passive (i.e. less air conditioning) systems use less energy. Temperature monitoring studies have, however, shown that indoor temperature is related to house age (Oreszczyn et al., 2006) and dwellings built before 1914 have been found to be 3℃ warmer than those built after 1970 (Hunt and Gidman, 1982) although this is partially related to a greater proportion of centrally heated dwellings in new builds this suggests that more energy is required to heat older homes.

4) Wall type is a description of how a dwelling is constructed. Before 1930 UK dwellings were predominantly built without a cavity between bricks. Since 1930 cavity wall construction has been widespread. Wall type and house age are therefore strongly linked. Solid walls have a higher U-value than cavity walls and are much harder to insulate. Changes to building

regulations have required that cavities are filled with insulation since 1990 (Figure 2-6). Many dwellings built before 1990, however, have also had cavity wall insulation added to reduce the heat loss through walls. Wall type is expected to influence indoor air temperature as wall type effects the U-value of the building fabric of the dwelling and consequently the amount of heat loss. Dwellings built using solid wall construction, have been found to have lower indoor temperatures than dwellings with other wall types (Oreszczyn et al., 2006).

Figure 2-6. Schematic of cavity wall construction

5) Heating type is related to whether dwellings are heated primarily via central heating or fixed heaters. Centrally heated dwellings are expected to be more uniform in temperature than those heated without central heating. Centrally heated dwellings have been found to be warmer than those without central heating both downstairs (2.4℃) and upstairs (3.7℃) (the sample was approximately 50% centrally heated (Hunt and Gidman, 1982). The type of fuel used for space heating has been shown to significantly impact on the cost of heating with electric heating having the highest and gas having the lowest cost (Meier & Rehdanz, 2010).

The relationship between energy use and technical descriptors are not always clear, for example, the type of heating in a dwellings has been shown to influence occupant behaviour (Guerra-Santin & Itard, 2010) and consequently it cannot be clear whether the behaviour or the heating system has the greatest impact on energy use. Analysis based on CDEM, however, concludes that approximately 40% reduction in CO_2 emissions are feasible through building fabric interventions (Firth & Lomas, 2009).

2.5.2 Social descriptors

Social descriptors are those that relate to the occupants and household composition, these include household income and the number of people living in a dwelling. Six social descriptors are described with reference to previous studies and their potential impact on energy use and indoor temperature is discussed.

1) The tenure of a dwelling, whether it is owned by the occupier or rented, relates to energy use by indirect means. Much of the variation in energy use and indoor temperature that relates to tenure is a result of the ability of household occupants to make energy efficiency improvements to their dwellings and therefore is related to technical differences between dwellings. For example, occupants living in rented accommodation may not be allowed (or it may not make financial sense due the length of payback) to make changes to the building fabric and landlords who do not live in the dwelling have no financial motivation to make energy efficiency changes if they are not paying energy bills. Rented houses are often less insulated than privately owned dwellings and consequently require more energy to heat (Druckman & Jackson, 2008). Meier and Rehdanz (2010), however, suggest that heating expenditure tends to be higher in dwellings which are owner occupied than rented, this is likely to be related to these homes being larger and consequently having greater heat loss. Previous temperature monitoring studies have not reported the impact of tenure on winter temperatures.

2) The employment status of household occupants is expected to influence the heating pattern used in the household and therefore the indoor

temperature. It is expected that occupants who are at work for a long time each day are likely to have shorter heating periods than individuals who do not work (for example those that are retired). Dwellings with a greater number of retired occupants spend less on energy as they tend to heat less of the home (Meier & Rehdanz, 2010).

3) It is expected that the age of household occupants is related to indoor temperature. For example, older occupants may also be less active and require higher temperatures. Occupants above 60 are also more likely to be retired which may result in longer heating periods and higher average temperatures. Survey research has shown that heating expenditure increases with the average age of occupants but that it decreases again for some retired occupant groups as less of the home is heated (Meier & Rehdanz, 2010). Temperature monitoring studies however have contradicting results relating the impact of age of occupants. Hunt and Gidman (1982) suggesting that houses with occupants over 65 years old were cooler than those with younger occupants while Oreszczyn et al. (2006) found that living room temperatures are warmer in dwellings with occupants over 60 years old than those with younger occupants but that bedrooms are cooler in the dwellings occupied by those over 60. This may be related to the different monitoring methods used in these two studies. Oreszczyn et al. (2006) report average temperature during the day in living rooms and during the night in bedrooms while Hunt and Gidman (1982) measured spot temperatures which do not take into account the length of time each space is heated.

4) The number of children in the dwelling is expected to influence the occupancy of the dwelling and therefore the heating practices that are used by occupants. For example, households where no children are present may not require heating until they arrive home from work which may be a number of hours after children arrive home from school. This may result in shorter heating periods and consequently lower average temperatures. Heating expenditure has been found to increase with the number of children

present in the dwelling (Meier & Rehdanz, 2010). Hunt found that average temperature was slightly (0.7℃) higher in dwelling s with children compared to those inhabited only by adults.

5) Household size is the number of occupants that live in a dwelling. A higher number of occupants living in a dwelling has been found to increase energy use (Steemers & Yun, 2009). This is probably a result of an increased length of time each day that the dwelling is occupied. Dwellings with a high number of occupants may also have higher indoor temperatures due to occupant heat gains. Top down modelling has shown that dwellings with more occupants use more energy in total but less per person that those with fewer occupants (Lenzen et al., 2004). Temperature monitoring, however, has shown little difference in average indoor temperatures between dwellings with varying household sizes (Oreszczyn et al., 2006).

6) Income has been found to have a direct relationship with heating energy expenditure with higher income groups using more energy, however, much of this higher energy use is related to households with higher incomes owning more appliances and income is therefore a less significant driver of energy use for space heating (Meier & Rehdanz, 2010) (Lenzen et al., 2004). Contrary to these results multiple regression analysis undertaken on gas consumption figures alone has indicated gas consumption is related to income, as this work used the median income for lower level super output area this result may be related to households with higher incomes living in larger homes (Morris et al., 2012).

Energy use in a dwelling is related to the complex interaction between built form, location, occupants, heat systems and energy costs (Wright, 2008). It is therefore difficult to remove the potential interactions between the technical and social descriptors for example income is a social descriptor but it has been shown to have an indirect relationship with energy use as a result of higher income families living in larger dwellings (Steemers & Yun, 2009).

2.6 Heating practices in domestic dwellings

Previous research has concluded that both technical and social determinants influence energy use and indoor temperatures in domestic dwellings. Energy modellers have shown that energy models are sensitive to changes in the heating practices used by household occupants. Heating practices are defined as the interactions between household occupants their heating systems that are used to control indoor temperatures.

2.6.1 Daily heating period

Daily heating period is the length of time that a dwelling is heated each day. For example, if a dwelling is heated between 6 o'clock and 8 o'clock in the morning and then 4 o'clock and 10 o'clock in the evening the daily heating period would be eight hours per day. The heating period in a dwelling is usually a result of the on and off times programmed into the boiler by the household occupants.

Length of heating period has been found to be related to energy costs (Guerra-Santin & Itard, 2010), this work also concluded that dwellings which turned on heating manually had shorter heating periods than those who controlled heating using a programmer. House type was also shown be correlated with length of daily heating period (ibid). Dwellings that are less thermally efficient require longer heating periods as more heat is lost through the building fabric and consequently heating is required for a longer time each day to provide comfortable indoor temperatures. Daily heating period has been estimated using temperature data collected in 358 homes (Shipworth et al. 2010). The estimated heating period was 8.3 hours per day and a variation between 4.7 to 12.7 hours per day was observed. These estimations were calculated by assuming that indoor temperature would fall when the heating system was not active. It was recognised that this does not account for periods of secondary heating or high heat gains due to solar radiation or high numbers of occupants. Despite its link with energy consumption very few studies have been undertaken to identify the length of daily heating period and therefore, further research is required in this area.

Although the length of the heating period has been estimated using temperature data, the time of heating periods were not reported. If energy efficiency technologies for space heating, such as ground source heat pumps, are to become more prevalent this will lead to an increase of electric heating. It is important to establish, therefore, not only the length of heating period but when the heating periods start and finish. This is an area where more research is required.

2.6.2 Demand temperature

Demand temperature is the temperature to which occupants heat their homes. This is often controlled by a thermostat and in previous work the term thermostat setting has been used. This is however, misleading due to the lack of correlation between thermostat setting and achieved temperature found in previous research (Shipworth et al., 2010).

Demand temperature has an impact on energy use for space heating as it directly affects the difference between outside and inside temperature (CIBSE, 1999). This has been demonstrated experimentally by MacKay (2008) who found that turning down the thermostat from 20℃ to 17℃ reduced the e nergy required to heat his house by 30%. This figure cannot be used as representative as it was only tested in one property. Karlsson & Moshfegh (2006) tested this theory using the dynamic simulation program ESP-r. Twenty low energy homes were monitored to find out how energy was used. One of the properties was modelled and various input parameters were changed to identify their impact on total energy use. Initially a thermostat set point of 21℃ was used. It was found that when the heating set point was reduced to 18℃ the energy required to ma intain the indoor temperature was reduced by 28%. It is noted that the model was not typical of buildings in the UK housing stock as it was a low energy building predominately heated by heat gains from occupants and appliances. The 28% reduction in energy, however, is similar to that found by MacKay which suggests that lowering the demand temperature will reduce energy use in a wide range of house types.

In the Netherlands self-report surveys suggested that 74% of households used a maximum thermostat setting of 19-20℃, the thermost at setting was found to influence energy use but not as strongly as the length of the heating period (Guerra-Santin & Itard, 2010). Steemers and Yun (2009) argue that demand temperature is not a behaviour but a consequence of external factors such as external temperature and the quality of thermal insulation of the building fabric. It was found that only 10% of the variation in heating energy was explained by difference in reported thermostat setting. This finding differs from other studies discussed here and is evidence that further research in this area is merited.

Shipworth et al. (2010) used temperature data to estimate thermostat settings and found that the average setting was 21.1℃, this compared to 19.0℃ which was reported by participants, no statistically significant relationship was found between reported and estimated thermostat settings. This questions either whether occupants are aware of the thermostat setting or the technique used to estimate the thermostat setting was accurate.

Research into reported thermostat settings in 1984 and 2007 suggests that thermostat settings have not changed over time (Shipworth, 2011). This research, however, was based on self-report thermostat setting which has been shown to have no correlation with estimated thermostat settings based on measured temperature data (Shipworth et al., 2010). It is also noted that during this time the proportion of centrally heated dwellings in the housing stock has dramatically increased (DECC, 2011) and temperature monitoring research has shown that rooms heated by fixed heaters are warmer than those in centrally heated dwellings (French et al., 2007).

The identification of the ‘thermostat setting’ in homes is complicated further as many domestic properties do not have only have room thermostats but use thermostatic radiator valves (TRVs) which control the temperature in each room but cannot be set to a specific temperature value. Studies aiming to identify the indoor temperatures of properties tend to monitor temperature in one or two rooms and are unable to address the variation of temperature throughout a whole dwelling.

2.6.3 Spatial variation of temperature

The spatial variation of temperature is the difference in temperature between different parts of the dwelling. BREDEM-based models assume that dwellings are split into two zones, a living area that is heated to 21℃ and the rest of the dwelling including bedrooms and bathrooms that are heated to 18℃. The increased prevalence of central heating and the use of thermostatic radiator values (TRVs) brings into question this assumption and temperature monitoring studies have found that the temperature difference between different rooms in the dwelling is very variable (DECC, 2009). Few temperature monitoring studies, however, have monitored temperature in every room in a house and therefore there is a lack of empirical evidence in this area.

2.6.4 Heating season

Heating season is the length of the year that dwellings are heated. For example, if heating is used from the beginning of October and until the end of February the heating season is 5 months. The increased energy consumption due to a longer heating season is partly dependent on external temperature. The greater the difference between indoor and outdoor temperature the more energy is required to heat the dwelling. Consequently, the relationship between heating season and heating related energy consumption is not linear.

French et al. (2007) monitored 397 homes in New Zealand for a year. 10 minute temperature data was measured in the living room and main bedroom. Variations in the winter heating period were calculated. The majority of homes were heated for 6 to 7 months; however, some properties were heated for a full 12 months and others as little as 3 months. The New Zealand housing stock and climate differs from the UK; however, the scale of variation in behaviour illustrates the difficulty in predicting this behaviour in UK homes. The length of the heating season has not been analysed in UK temperature monitoring studies and is an area for further research.

2.7 Summary

The UK housing stock is the second most significant energy sector in the UK. Space heating accounts for approximately 66% of the energy used in domestic dwellings.

Research into the influence of social and technical household descriptors on energy use for space heating and indoor temperatures in domestic dwellings can be categorised into three areas; large-scale surveys, energy modelling and temperature monitoring. There have been few large-scale UK based survey studies in which energy data has been collected and although studies from different countries make similar conclusions, the UK housing stock and climate differs significantly from other countries and it is, therefore, suggested that this is an important area for future research.

Energy models are important tools in understanding the drivers of energy use and the impact of energy saving initiatives and policy but many of these models use standard heating practices which could result in misleading predictions. BREDEM-based models use standardised heating practices and an idealised temperature profile to calculate average monthly temperatures, there is potential to improve the assumptions relating to how heating systems respond using monitored temperature data.

More research is required to understand the variation of heating practices that are used in the housing stock and to explore whether the variation is related to social and technical household descriptors. This research could be used to improve the assumptions used in energy models and ensure that the predictions of energy models are accurate and robust.

Previous temperature monitoring studies have begun to provide insight into the temperatures to which UK dwellings are heated but few samples have been large enough to explore the influence of technical or social descriptors on average indoor temperatures. One exception to this was a study that monitored indoor temperature in over 1600 dwellings and reported average temperatures according to property and household characteristics (Oreszczyn et al., 2006), these results are important but limited in their application to the wider housing stock as the sample was limited to low income dwellings and other research has shown that there is a strong relationship between energy use for space heating and income and consequently indoor temperatures. Temperature monitoring research has demonstrated the potential to estimate heating practices, results of daily heating period and thermostat setting have been reported but length of heating season, and start and end times of heating have not been addressed.

It is suggested that heating metrics which define the range and variation in how occupants heat their homes and the temperatures which are delivered by heating systems should be developed to increase the knowledge of indoor temperatures in domestic dwellings. This will provide a valuable resource for the energy modelling community which will enable researchers to develop energy models which are able to more accurately predict energy use across different sectors of the housing stock.

3 Methods – Data collection, processing and analysis

The average winter temperatures and heating metrics developed and calculated in this thesis are based upon temperature data collected during a large-scale city-wide survey in Leicester, UK. This chapter describes the data collection, processing and analysis techniques related to the temperature monitoring and survey. Section 3.1 describes the data collection with specific reference to temperature monitoring. Section 3.2 describes the data processing and outlines the rationale for exclusions. Section 3.3 outlines the sample with reference to a number of key technical and social descriptors and describes some of the limitations of the data set. To understand how the results can be applied to Leicester, where the data was collected, and to England as a whole, the composition of the data is compared to the 2001 census and data collected as part of the 2009 English House Condition survey. Section 3.4 discusses the complexity of the data and discusses a number of anomalies within the data. Section 3.5 introduces the data analysis techniques used in the following results chapters and provides reasons for their use. Section 3.6 is a summary of the discussion in this chapter.

3.1 Data collection and cleaning

3.1.1 Face-to-face surveys

The indoor temperature measurements were taken as part of the 4M Project. The 4M Project - Measurement, Modelling, Mapping and Management (4M): An Evidence-Based Methodology for Understanding and Shrinking the Urban Carbon Footprint – is a research project between four Universities funded through the EPSRC, a UK Research Council (Lomas et al., 2011). 4M is studying CO_2 emissions sources and sinks within urban areas as 80% of the population of the UK live in urban areas and approximately 58% in cities (ONS, 2009a). The research aims to be representative of the urban environment and Leicester city was chosen as a case study. An integral part of this work was a large-scale city-wide housing survey carried out in Leicester, UK in 2009-2010.

Households were selected randomly after stratifying by percentage of detached dwellings and percentage of households with no dependent children. Initially 1000 households were approached to take part in the study. Due to the scale of the survey the interviews were conducted by the National Centre for Social Research (NatCen) (NatCen, 2011). NetCen has experience of delivering large-scale surveys and used trained surveyors. The surveyors did not have any specific prior knowledge of building energy or carbon footprints. 575 households (approximately 1 in 200 homes in Leicester) took part in the survey which covered a number of topics that relate to the direct carbon footprint of households including transport, management of green space and domestic energy use as well as socio-demographic information. The rough location of each of the households interviewed is indicated, with respect to the boundary of Leicester city (Figure 3-1).

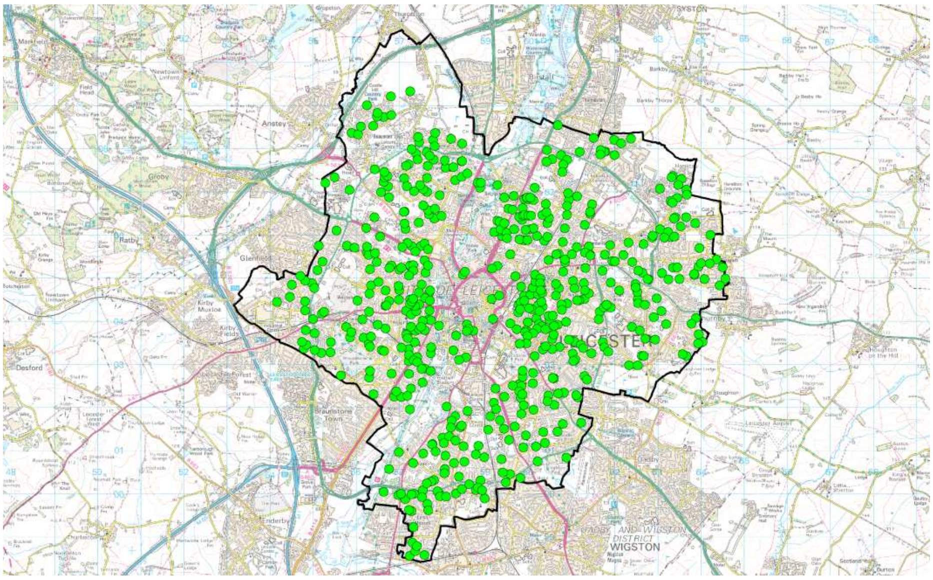
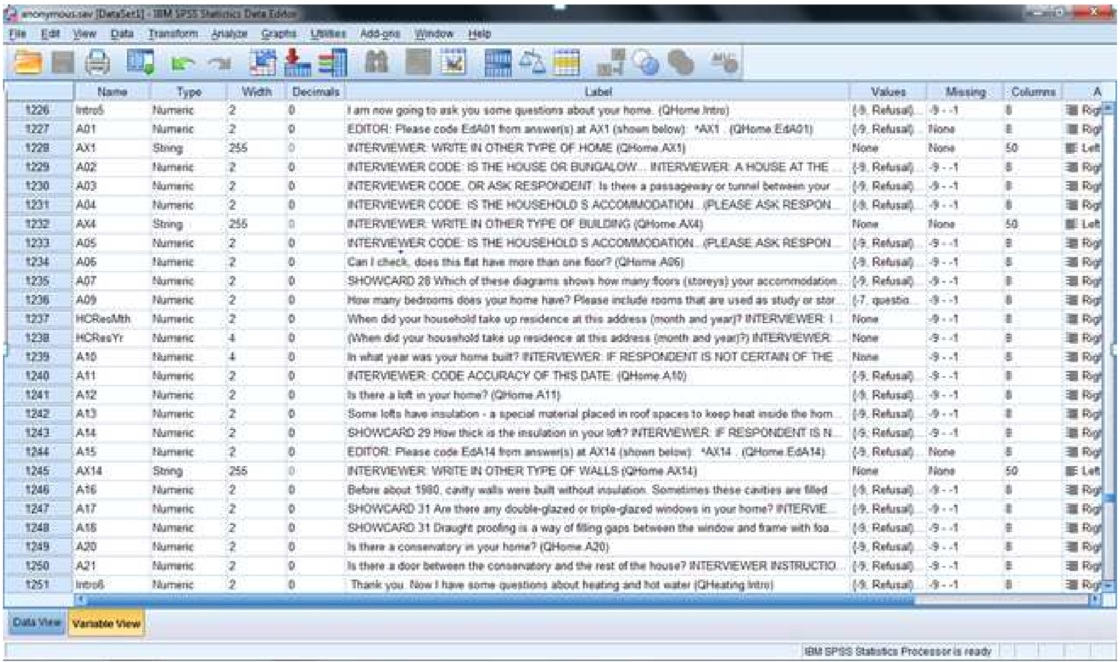


Figure 3-1. The 575 households surveyed and there relative position to the Leicester city boundary (from Lomas et al., 2011).

The surveyors used computer aided personal interviewing (CAPI) for face-to-face interviews. The responses to the questions were then coded on a numerical scale and inputted into SPSS (Figure 3-2). For this work the questions which related to the people living in the dwelling and those which were related to building energy were the most relevant. The questions about green space management and travel were not used.



	Name	Type	Width	Decimals	Label	Values	Missing	Columns	A
1226	Intro5	Numeric	2	0	I am now going to ask you some questions about your home. (QHome.Intro)	{-9, Refusal}...	-9 - -1	8	Rig
1227	A01	Numeric	2	0	EDITOR: Please code EdA01 from answer(s) at AX1 (shown below): ^AX1 . (QHome.EdA01)	{-9, Refusal}...	None	8	Rig
1228	AX1	String	255	0	INTERVIEWER: WRITE IN OTHER TYPE OF HOME (QHome.AX1)	None	None	50	Left
1229	A02	Numeric	2	0	INTERVIEWER CODE: IS THE HOUSE OR BUNGALOW... INTERVIEWER: A HOUSE AT THE ...	{-9, Refusal}...	-9 - -1	8	Rig
1230	A03	Numeric	2	0	INTERVIEWER CODE, OR ASK RESPONDENT: Is there a passageway or tunnel between your ...	{-9, Refusal}...	-9 - -1	8	Rig
1231	A04	Numeric	2	0	INTERVIEWER CODE: IS THE HOUSEHOLD S ACCOMMODATION... (PLEASE ASK RESPON...	{-9, Refusal}...	-9 - -1	8	Rig
1232	AX4	String	255	0	INTERVIEWER: WRITE IN OTHER TYPE OF BUILDING (QHome.AX4)	None	None	50	Left
1233	A05	Numeric	2	0	INTERVIEWER CODE: IS THE HOUSEHOLD S ACCOMMODATION... (PLEASE ASK RESPON...	{-9, Refusal}...	-9 - -1	8	Rig
1234	A06	Numeric	2	0	Can I check, does this flat have more than one floor? (QHome.A06)	{-9, Refusal}...	-9 - -1	8	Rig
1235	A07	Numeric	2	0	SHOWCARD 28 Which of these diagrams shows how many floors (storeys) your accommodation...	{-9, Refusal}...	-9 - -1	8	Rig
1236	A09	Numeric	2	0	How many bedrooms does your home have? Please include rooms that are used as study or stor...	{-7, questio...	-9 - -1	8	Rig
1237	HCResMth	Numeric	2	0	When did your household take up residence at this address (month and year)? INTERVIEWER: I...	None	-9 - -1	8	Rig
1238	HCResYr	Numeric	4	0	(When did your household take up residence at this address (month and year)?) INTERVIEWER: ...	None	-9 - -1	8	Rig
1239	A10	Numeric	4	0	In what year was your home built? INTERVIEWER: IF RESPONDENT IS NOT CERTAIN OF THE ...	None	-9 - -1	8	Rig
1240	A11	Numeric	2	0	INTERVIEWER: CODE ACCURACY OF THIS DATE: (QHome.A10)	{-9, Refusal}...	-9 - -1	8	Rig
1241	A12	Numeric	2	0	Is there a loft in your home? (QHome.A11)	{-9, Refusal}...	-9 - -1	8	Rig
1242	A13	Numeric	2	0	Some lofts have insulation - a special material placed in roof spaces to keep heat inside the hom...	{-9, Refusal}...	-9 - -1	8	Rig
1243	A14	Numeric	2	0	SHOWCARD 29 How thick is the insulation in your loft? INTERVIEWER: IF RESPONDENT IS N...	{-9, Refusal}...	-9 - -1	8	Rig
1244	A15	Numeric	2	0	EDITOR: Please code EdA14 from answer(s) at AX14 (shown below): ^AX14 . (QHome.EdA14)	{-9, Refusal}...	None	8	Rig
1245	AX14	String	255	0	INTERVIEWER: WRITE IN OTHER TYPE OF WALLS (QHome.AX14)	None	None	50	Left
1246	A16	Numeric	2	0	Before about 1980, cavity walls were built without insulation. Sometimes these cavities are filled ...	{-9, Refusal}...	-9 - -1	8	Rig
1247	A17	Numeric	2	0	SHOWCARD 31 Are there any double-glazed or triple-glazed windows in your home? INTERVIE...	{-9, Refusal}...	-9 - -1	8	Rig
1248	A18	Numeric	2	0	SHOWCARD 31 Draught proofing is a way of filling gaps between the window and frame with foa...	{-9, Refusal}...	-9 - -1	8	Rig
1249	A20	Numeric	2	0	Is there a conservatory in your home? (QHome.A20)	{-9, Refusal}...	-9 - -1	8	Rig
1250	A21	Numeric	2	0	Is there a door between the conservatory and the rest of the house? INTERVIEWER INSTRUCTIO...	{-9, Refusal}...	-9 - -1	8	Rig
1251	Intro6	Numeric	2	0	Thank you. Now I have some questions about heating and hot water (QHeating.Intro)	{-9, Refusal}...	-9 - -1	8	Rig

Figure 3-2. Interview questions as shown in the variable view in statistics package SPSS

Important details relating to the people living in each house included the number and age of each of the household members and the total household income. To reduce the length of the interview a number of questions were asked only to the person who answered the interview questions, the household representative person (HRP). These included questions about employment status.

The building energy questions were mostly concerned with the technical attributes of the building. Details regarding house type (i.e. detached, end-terrace), house age (year of construction), wall type (solid/cavity wall), type of heating system used and level of roof insulation were collected for each dwelling. Additionally, the HRP was asked how the heating systems were used i.e. when they were turned on and off and whether a particular thermostat setting was used.

During the survey participants were asked to take part in a number of follow-up activities including a more detailed travel survey, an appliance questionnaire, gas and electricity meter readings and indoor temperature monitoring.

3.1.2 Temperature measurements

Participants were asked to have a temperature sensor in their living room and main bedroom. At the time of the interviews 481 households agreed to the temperature follow-up. Sensors were placed in both the living room and the main bedroom in 469 households as a number of households that agreed to the temperature follow-up were not supplied with temperature sensors by NatCen interviewers.

Figure 3-3. Hobo data logger used to measure internal air temperature in 292 dwellings in Leicester City.

Hobo pendant temperature sensors were used to monitor indoor temperature every hour between July 2009 and March 2010 (Figure 3-3). The sensors were chosen for this study as they are small and unobtrusive, they do not require remote sensing capability or additional onsite data logging equipment and they are robust and waterproof and are, therefore, unlikely to get damaged which reduces the chance of data loss.

Hobo pendant temperature sensors use a thermistor to measure temperature. A thermistor is a resister whose resistance changes significantly with temperature; the circuit in the sensor registers the difference in resistance as a temperature. Sensors are read via an optical connector and can be programmed to start at a time in the future. In this study each sensor was programmed to start on the 1st July at 12:00am, the sensors then logged temperatures each hour until the memory was full. 8K sensors were used which can store approximately 6,000 readings, the monitoring period was limited by the memory of the sensors. The sensors take spot measurements and are therefore are more susceptible to short term temperature spikes than temperature sensors which report an average temperature over the logging period.

The sensors were calibrated by Tempcon Ltd and found to be accurate to ±0.4℃ (Tempcon Instrumentation Ltd., 2010). According to the technical specifications Hobo pendent temperature loggers can measure temperature in the range between -20° to 70℃ and are accurate to ± 0.53℃ b etween 0° to 50℃ (ONSET, 2012) and are therefore appropriate for measuring the normal range of temperatures which are expected in domestic dwellings. The drift of the sensors is less than 0.1℃/year and consequently will not impa ct on temperatures measured in this study. The response time of the sensors in an airflow of 2 m/s is 10 minutes (to 90% of temperature) and submerged in water 5 minutes (to 90% of temperature) this is relatively slow but when only logging at hourly intervals does not limit the validity of results.

Guidance on the placement of sensors was provided by the interviewers and stated that the sensors should be placed away from heat sources and not in direct sunlight. This was to ensure that measurements related to air temperature. As the temperature sensors were place by household members and not trained researchers it is important to ascertain the possible error in temperature measurements which relate to where in the room the sensors were placed.

To understand this ‘placement error’ an experiment was undertaken. The experiment took place in a test house built according to 2002 housing regulations. 27 temperature sensors were placed in a grid in a single room. Each sensor was one meter apart and temperature was measured every five minutes for two days. Sensors placed very close to the ceiling measured temperatures more than 1℃ higher than those placed lower in the room (Figure 3-4). All other temperatures remained within 0.5℃ which is the specified accura cy of the sensors. It was therefore concluded that unless the sensors were placed within 15cm of the ceiling they would measure comparable temperatures. A detailed description of the experiment is given in Appendix 3.

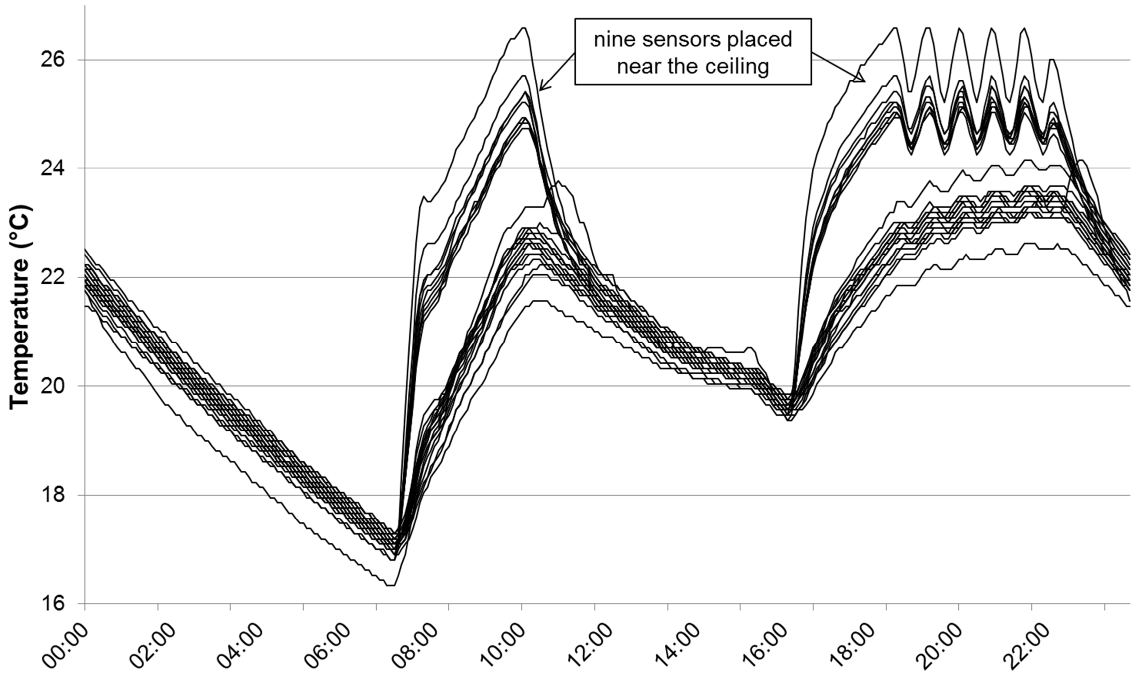


Figure 3-4. Temperature measurements taken in 27 positions in a single room at five minute intervals for one winter day.

At the end of the monitoring period prepaid envelopes were sent to each household with a request for Hobos to be returned. 620 Hobos were returned from 319 households. Hobo temperature sensors were downloaded one-by-one using an optical cable and Hoboware software. Each file was then saved to Excel sheets as raw data.

The outdoor air temperature used in this thesis was measured at hourly intervals at Leicester City Council's central weather mast at a height of 2m. The mast is located in the centre of the city and was therefore assumed to be an approximation of outside air temperature for all the dwellings (Figure 3-1). Average outdoor temperature measured in Leicester during the winter period analysed in this work (December 2009 – February 2010) was 2.3℃, which is colder than the average temperature in Leicester for the months of December to February (calculated for the period 2000-2009) of 4.6℃.

3.2 Data processing and cleaning

This section aims to show the plausibility of the temperature data which will be analysed in the following chapters. First, the decision making framework for the exclusion of erroneous data is described and examples of each of the reasons for exclusion is given. Second, examples of data anomalies which relate to occupant behaviour are shown to illustrate the complexity of the data and the challenge which the variability of occupant behaviour presents for data analysis.

3.2.1 Initial data processing

Data was downloaded from 312 households, 281 with both living room and bedroom sensors, 18 which only had living room sensors and 13 which only had bedroom sensors.

Two methods were used to identify problems in the data files and temperature measurements that made them unsuitable for further analysis. First, a programme was written in Visual Basic for Applications (VBA) to return the maximum, minimum and average temperatures for the whole monitoring period, the first date on the time stamp and the number of entries in each Excel file was also found.

Data files which returned the wrong initial date or more or less entries than expected were opened and the reasons for the anomalies identified. This process identified a number of data files with additional lines with no data. These lines were found to be related to periods where the timestamp was duplicated and were therefore removed.

Second, to ensure that the temperature readings were valid for further analysis graphs for each dwelling relating to a whole winter month were plotted showing temperature traces for living room, bedroom and outdoor air temperature (Appendix A.1.1). These were then studied by eye to identify any anomalies which would cause the results to be incorrect. Where erroneous temperature traces were clearly identifiable these were excluded, however, in some cases subtle judgements were required. When this was the case a second experienced researcher was consulted to ensure that reasonable choices were made.

3.2.2 Rationale for exclusions

As each sensor was placed by the household occupants and not trained researchers there was scope for placement errors. A number of these were identified in the temperature traces and will be described. The number of dwellings which were removed from the sample for each reason is shown (Table 3-1).

Table 3-1. Number of households returning sensors and reasons for exclusion from final data set

	Number of households
Households returning at least one sensor	312
Living room only	18
Bedroom only	13
Thermal separation	14
Sensors placed together	5
Sensors moved	2
Timing errors	5
Sensor in unheated space	3
Sensor in direct sunlight	3
Total households excluded	63
Final data set	249

There were seven reasons why dwellings were excluded from analysis and these are discussed below. The examples in this chapter and later are evidence that all temperature traces measured in domestic dwellings are unique and show some of the problems which relate to the analysis of real world data, especially in this case where sensors were placed by household occupants and not trained researchers.

3.2.3 Reason 1 - Data only available from one sensor in a dwelling

A single sensor was returned from 31 households. So that temperatures in both spaces could be compared it was decided that only dwellings where data was available for analysis from both living rooms and bedrooms would be included. For example, if the number of sensors returned from flats included 32 living rooms but only 19 bedrooms, when comparing average temperatures measured in the living room and bedroom of all house types the average bedroom temperature would be lower than expected due to the reduced number of bedrooms in flats which are expected to have the highest indoor temperatures.

The 31 dwellings where only one sensor was returned were therefore excluded. During the exclusion process if a problem was found with a single sensor returned from a dwelling both sensors were excluded.

3.2.4 Reason 2 - Thermal separation

Thermal separation was observed when either the living room or the bedroom sensor showed more variation than the other (Figure 3-5). In these dwellings one of the sensors may have been placed in an unheated room (or in a drawer) which insulated it from the temperature swings relating to heating and cooling. Fourteen dwellings were excluded from the final data set as a result of thermal separation.

An example of a dwelling where thermal separation was observed is shown below (Figure 3-5). The heating is used in this dwelling once each day as the living room temperature clearly indicates. The bedroom temperature shows little or no evidence of heating which suggests that the sensor is insulated from the temperature variation in the space or that the radiator situated in the bedroom is turned off. This reading therefore gives little or no insight into the heating patterns used this home.

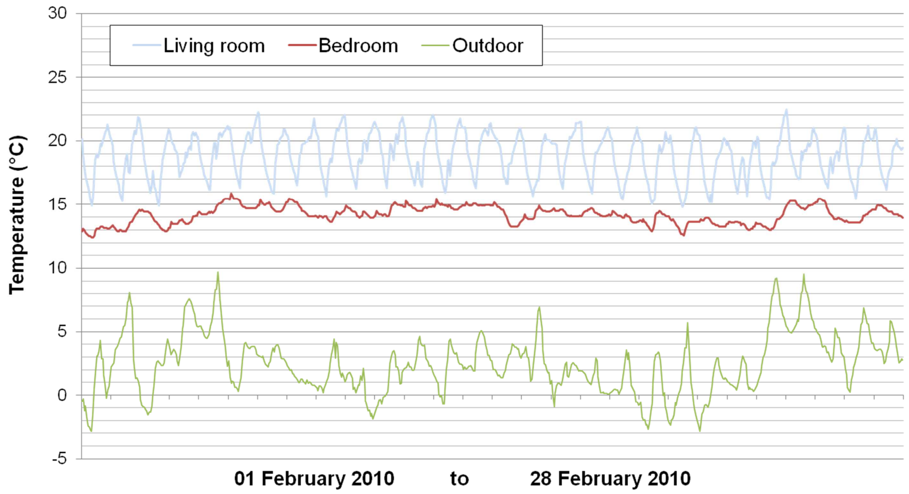


Figure 3-5. Temperature traces from one dwelling for the period 1st February to 28th February 2010 showing an example of thermal separation.

Similarly Figure 3-6 depicts a bedroom which is responsive to heating but the living room temperature responds inconsistently to heating suggesting that the sensor is again shielded from the air temperature in the space. In this example the living room sensor may have been place in an unheated room, on the whole the room remains cold and unresponsive to heating but occasionally, maybe when internal doors are opened or TRVs altered, the temperature increases in line with the bedroom temperature.

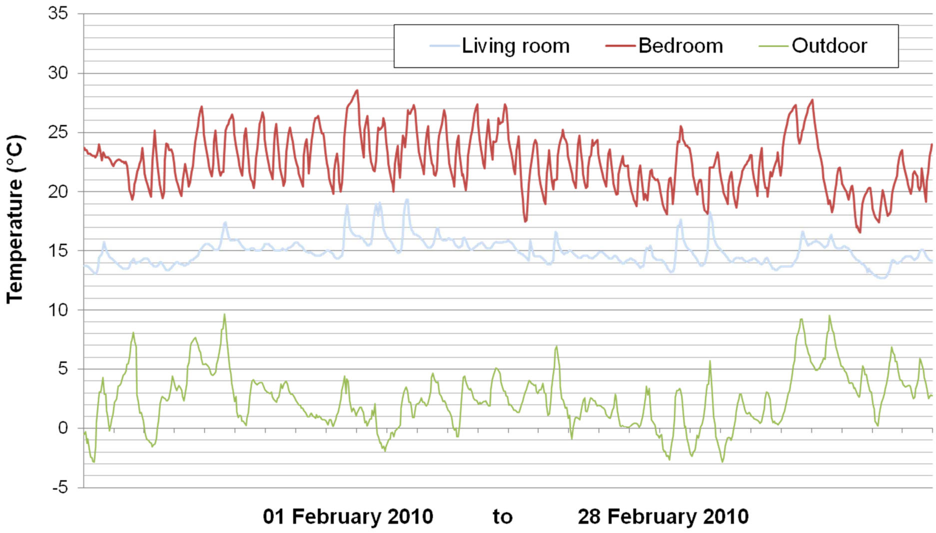


Figure 3-6 Temperature traces from one dwelling for the period 1st February to 28th February 2010 showing an example of thermal separation.

3.2.5 Reason 3 - Sensors placed together

Sensors were assumed to be placed close together when the observed temperature traces in both rooms were very similar. The data from these dwellings was deemed unsuitable for analysis as there was no way of knowing which room the temperatures related to. Five dwellings were excluded as the sensors were placed together.

Figure 3-7 shows an example of a dwelling where the sensors were placed together as it can be seen that the sensors record almost identical temperatures for the whole of the monitoring period. In this dwelling the sensors are measuring indoor temperature in a space which is heated each day but it is not possible to know which space and therefore temperatures are not comparable to those measured in other dwellings.

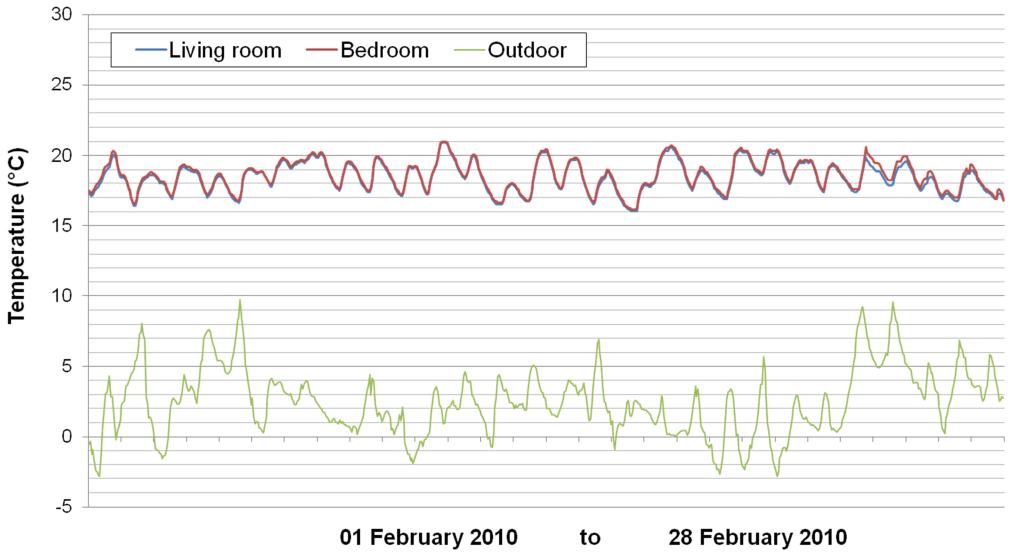


Figure 3-7. Temperature traces from one Leicester dwelling during February 2010. An example of the two sensors being placed close together.

3.2.6 Reason 4 - Sensors moved during period of analysis

Sensors which were moved during the analysis period were excluded from the sample as it is not possible to compare temperatures across the study period. Two dwellings were removed from the analysis as a result of one of the sensors being moved.

This type of exclusion highlights the difficulty in assessing data of this type and in each case a judgement call was necessary as in some cases a step change in temperature can relate to occupant behaviour, for example an increase in the thermostat setting may look like the sensor has been moved but this is genuine occupant behaviour; which this study aims to capture.

In the example below, during the first half of the month both temperature sensors are recording temperature with a small daily swing (Figure 3-8). After a fortnight the living room temperature starts to vary more noticeably throughout the day. Whereas the bedroom sensor responds to heating consistently throughout the whole period. In this case it was decided that the living room sensor was moved and therefore the household was excluded.

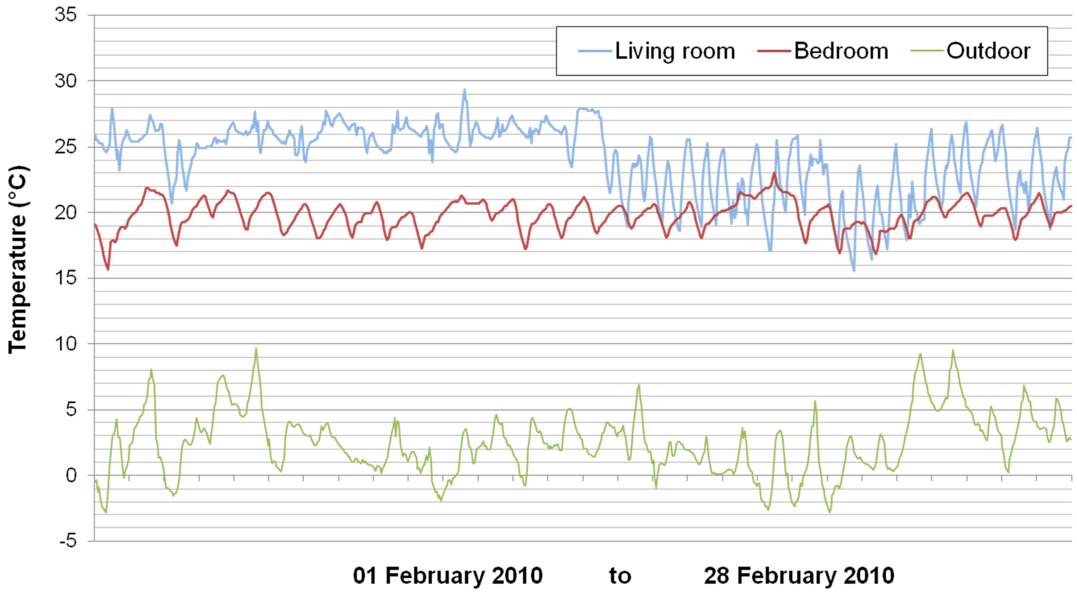


Figure 3-8. Monthly plot of a single dwelling where the living room sensor was moved during the analysis period

3.2.7 Reason 5 - Sensor timing error

When the internal clock of the sensor was not set up correctly or there was drift, i.e. the clock was slow or fast, the resulting temperature measurements were excluded as it was not possible to be certain of the time at which the temperatures were recorded. Five dwellings were excluded as a result of sensor timing errors.

In the example below, the living room temperature increases during the day in a typical double heating pattern but the bedroom temperature relates to a different time stamp and therefore the temperatures go in and out of phase (Figure 3-9).

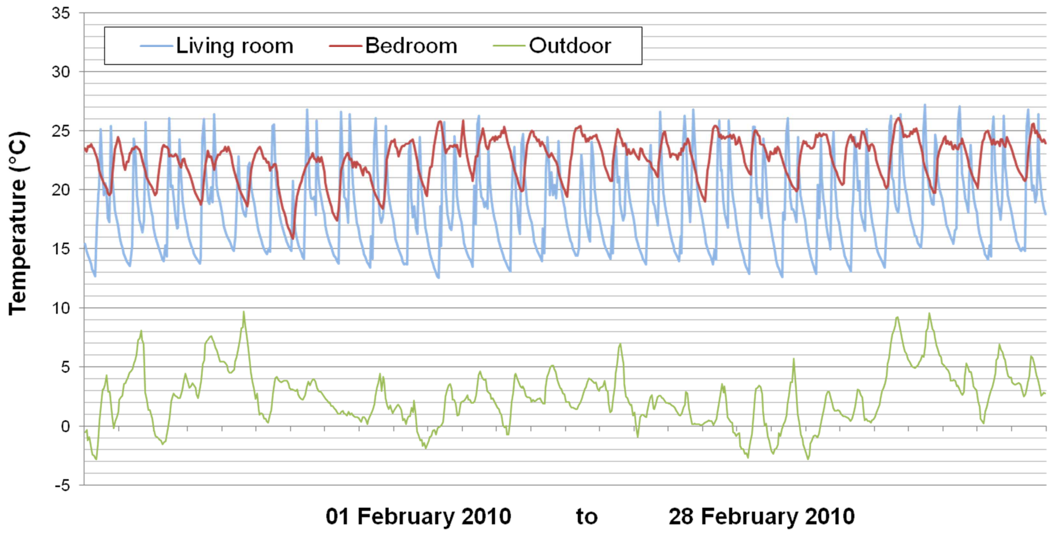


Figure 3-9. Monthly plot shown a dwelling with sensors which had timing errors.

3.2.8 Reason 6 - Sensors in unheated spaces

The temperature traces from unheated spaces were seen to be very dynamic and to follow the outdoor air temperature closely. These sensors may have been placed in porches, cellars or garages and the data recorded is therefore not relevant to this study (Figure 3-10). Three dwellings were excluded because one or both of the sensors were in an unheated space.

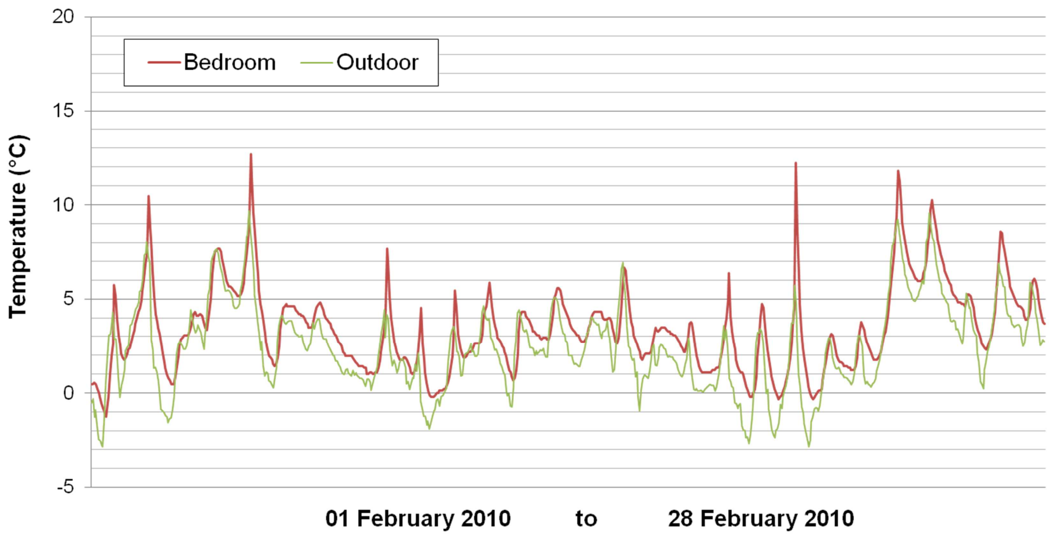


Figure 3-10. Temperature traces from a single Leicester dwelling during February 2010 showing temperature sensors placed in an outside space.

3.2.9 Reason 7 - Sensors in direct sunlight

Sensors placed in direct sunlight can distort temperature readings with sudden peaks and will result in high average temperatures. To understand the difference in response between a sensor placed in direct sunlight and one which is measuring temperature in a room with solar gain an experiment was carried out.

Two sensors were placed on a window sill in a south facing room. One of the sensors was shielded from direct sunlight (Figure 3-11). Temperatures were recorded for 6 days before the sensors were placed together. On days with high solar irradiance temperatures recorded by the sensor which was in direct sunlight increased rapidly to temperatures more than 15℃ higher than those recorded by the shaded sensor. This was taken into account when identifying sensors which were placed in direct sunlight.

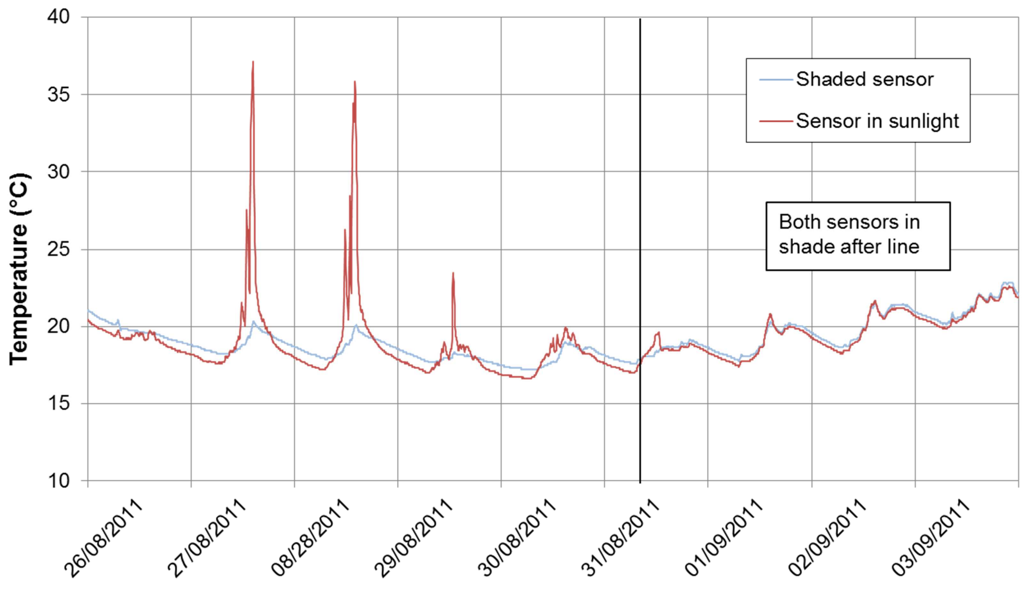


Figure 3-11. Results of experiment to show the effect of direct sunlight on temperature measurements.

In the winter the levels of solar radiation are lower than during summer months and the days with clear skies are fewer. In the example below, in the first half of the month both sensors show no sign of solar gain (Figure 3-12). During this time the levels of solar radiation was low. During periods of high solar radiation, however, the temperature measured by the bedroom sensor can be seen to increase dramatically by up to 15℃. Three dwelling s were removed from analysis as a result of sensors being paced in direct sunlight.

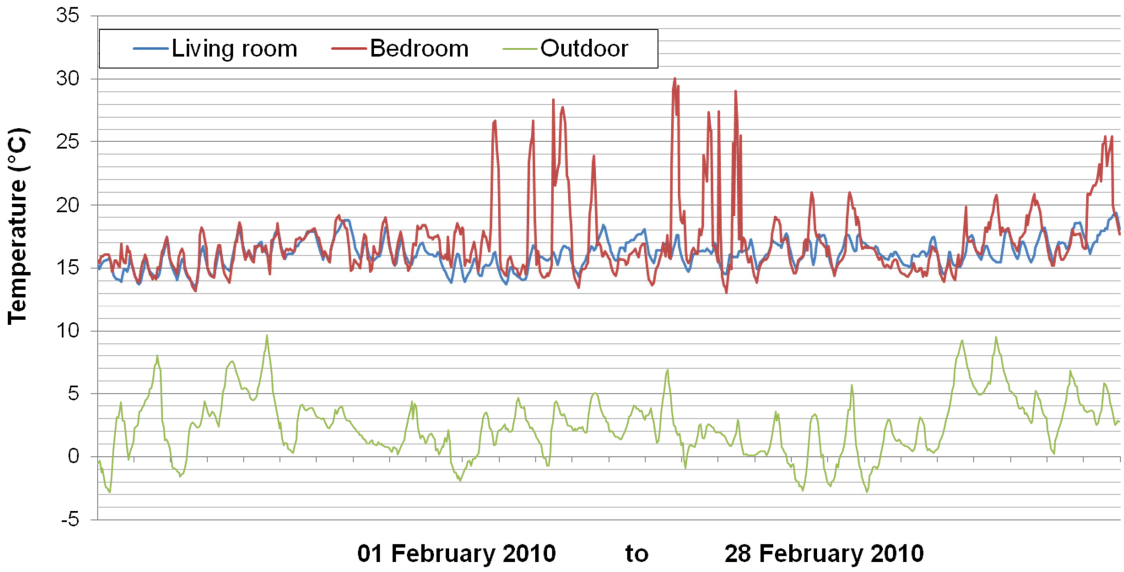


Figure 3-12. Monthly temperature plot for a single dwelling showing a bedroom sensor placed in direct sunlight

3.3 Sample composition and limitations

A number of limitations and errors relating to the accuracy of the data collected during face-to-face interviews were discovered. The Living in Leicester (LIL) survey covered a wide range of topics including building characteristics, socio-economic data about the occupants, management of green space and travel. Only the variables which have been highlighted as important in energy or temperature research were used and these were studied to identify their suitability for further analysis.

3.3.1 Data cleaning process

A number of errors and limitations were identified and these are outlined in this section. Some of the errors were related to the survey being carried out by interviewers with no background in buildings or energy research, for example, in response to the question "Which of these best describes the walls in your building. Please ignore any external render and the internal finish, which is usually plaster or plasterboard?" Since the 1930's, solid wall construction has become rare, however, a significant number of households with dwellings built after 1930 stated that their properties were built with 'solid' wall construction. The wall type response for every dwelling was therefore checked.

Google street view was used to locate each dwelling and where possible identify the type of wall construction based on the brick work and age of the property. Cavity walls generally have a brick pattern with each brick offset half a brick from the layer below, called Stretcher or Running bond. Solid walls have a brick turned which ties the two layers of brick work together this brick pattern is called a Flemish bond (Figure 3-13). The wall type reported in the survey was changed only when it was certain that the original response was incorrect.

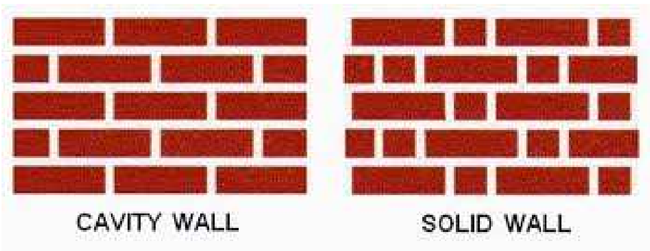


Figure 3-13. Brick work of dwellings built with cavity and solid walls.

Previous research has shown that the floor area of dwellings is one of the most significant drivers of energy use for space heating. Floor area data, however, was not collected during the face-to-face interview. Researchers working on the 4M project used Geographic Information Systems (GIS) to estimate the floor area of dwellings based on the perimeter of each dwelling. This method, however, could not be used to estimate floor area of individual flats within larger buildings or dwellings where the number of floors was not known. As only a partial dataset based on a number of assumptions was available it was decided to not include floor area as a descriptor in this analysis. It is noted that floor area is likely to have an impact on indoor temperature as larger dwellings will have a large area of exposed wall; these dwellings are consequently likely to have lower average temperatures. House type, however, is expected to identify some of the variation in indoor temperatures which is related to floor area, detached dwellings for example will have the greatest floor area on average and flats the smallest (EHS, 2009). Consequently, although the omission of floor area data in this analysis weakens this work it does not invalidate the analysis altogether.

In the house type descriptor there were only four bungalows in the temperature sample. Bungalow was therefore not included as a separate house type but where the bungalow was detached or semi-detached it was included into these categories.

3.3.2 Key social and technical descriptors

After the exclusions described in Section 3.2, the sample comprised of 249 households (i.e. 80% of the households from which sensors were downloaded). Temperature data from both the living room and bedroom is available for analysis from all 249 households. Initially, the sample is described to show the number of dwellings in each technical and social category here in called descriptors.

The seven technical and social descriptors shown here were chosen as these were subsequently found to have a statistically significant relationship with mean winter indoor temperature (see Section 4.2) and it is therefore important to establish how far the analysis of these descriptors and their sub-categories can be taken. The number of dwellings in each descriptor and sub-category is shown in Table 3-2.

Five house types were found in the survey; detached (10%), semi-detached (46%), end-terrace (10%), mid-terrace (24%) and flats (10%) (as noted previously bungalows were included as detached of semi-detached as appropriate). The smallest sample size relating to house type are end-terrace and flats with 24 dwellings each. The sample included flats which were purpose built and converted, however, the sample sizes of these sub-categories of flats was deemed to be too small to identify any significant trends.

With the exception of the pre-1900 age range, all of the age ranges account for at least 12% of the sample. There are only 15 dwellings in the pre-1900 sub-category. The most significant house age in the sample are the dwelling built between 1920 and 1944 (31%). The newest dwellings, built since 1980 account for 13% of the sample.

There were three wall types in the sample, solid (43%), unfilled cavity (24%) and filled cavity (33%). Wall type and house age are related as before 1930 most dwellings were built with solids walls and before 1990 houses built with cavity walls did not usually have cavity wall insulation. Many of these properties have had insulation fitted retrospectively, other properties that have been built since 1980 had insulation fitted when they were built as a result of changes to the building regulations.

Table 3-2 Number of households where temperature data measured in living room and bedroom spaces in Leicester homes is suitable for analysis.

	Number of dwellings in sample/ percentage in sample											
	All dwellings		Detached		Semi-detached		End-terrace		Mid-terrace		Flats	
All	249	100%	26	10%	115	46%	24	10%	60	24%	24	10%
House age												
Pre1899	15	6%	1	0%	4	2%	1	0%	9	4%	0	0%
1900-1919	31	12%	3	1%	9	4%	1	0%	16	6%	2	1%
1920-1943	77	31%	7	3%	50	20%	5	2%	13	5%	2	1%
1944-1965	58	23%	4	2%	31	12%	6	2%	9	4%	8	3%
1966-1980	35	14%	4	2%	9	4%	7	3%	10	4%	5	2%
Post 1980	33	13%	7	3%	12	5%	4	2%	3	1%	7	3%
Wall type												
Solid wall	106	43%	9	4%	53	21%	6	2%	36	14%	2	1%
Cavity wall (unfilled)	61	24%	4	2%	24	10%	8	3%	13	5%	12	5%
Cavity wall (filled)	82	33%	13	5%	38	15%	10	4%	11	4%	10	4%
Tenure												
Own outright	97	39%	17	7%	47	19%	8	3%	20	8%	5	2%
Own with mortgage	78	31%	8	3%	39	16%	7	3%	18	7%	6	2%
Rent	74	30%	1	0%	29	12%	9	4%	22	9%	13	5%
Household size												
1	65	26%	6	2%	23	9%	6	2%	15	6%	15	6%
2	91	37%	9	4%	45	18%	10	4%	20	8%	7	3%
3	39	16%	3	1%	23	9%	4	2%	8	3%	1	0%
4	36	14%	4	2%	17	7%	2	1%	12	5%	1	0%
5+	18	7%	4	2%	7	3%	2	1%	5	2%	0	0%
Employment status												
Full time	102	41%	11	4%	51	20%	7	3%	26	10%	6	2%
Part time	31	12%	4	2%	10	4%	6	2%	10	4%	1	0%
Unemployed	15	6%	0	0%	7	3%	2	1%	2	1%	4	2%
Permanently unable to work	16	6%	1	0%	6	2%	1	0%	4	2%	4	2%
Look after family	4	2%	0	0%	4	2%	0	0%	0	0%	0	0%
Retired	68	27%	10	4%	32	13%	7	3%	13	5%	6	2%
Student	6	2%	0	0%	2	1%	1	0%	3	1%	0	0%
Other	7	3%	0	0%	3	1%	0	0%	2	1%	2	1%
Age of oldest occupant												
20	12	5%	1	0%	4	2%	2	1%	4	2%	1	0%
30	41	16%	2	1%	15	6%	6	2%	12	5%	6	2%
40	59	24%	5	2%	26	10%	4	2%	21	8%	3	1%
50	39	16%	3	1%	26	10%	2	1%	5	2%	3	1%
60	50	20%	8	3%	20	8%	3	1%	10	4%	9	4%
70	33	13%	5	2%	17	7%	3	1%	7	3%	1	0%
80+	15	6%	2	1%	7	3%	4	2%	1	0%	1	0%

Three types of tenure were found in the sample; households where the occupants own the dwelling outright (39%), households were the occupants are buying their dwelling with the help of a mortgage (31%) and rented dwellings (30%). The three sub-categories in the tenure descriptor are the most similar sample sizes of any of the descriptors.

The average household size or number of occupants per dwelling of the sample is 2.4 people. Dwellings with a household size of two (36.5%) and one (26.1%) are the most common in the sample. Only 7.2% of the households in the sample have five or more occupants (i.e. 18 dwellings).

The sample is dominated by participants who are either in full time employment (41%) or retired (27.3%). The employment status descriptor was based on the Household Representative Person (HRP), the individual that answered the survey questions and therefore does not represent every member of the household. Some of the employment status sub-categories, including those where the HRP looks after the family (4 dwellings), have small sample sizes (less than 10 households) and are therefore not expected to allow for meaningful analysis due to the effect of outliers. These sub-categories of employment status were, therefore, recoded into an ‘other’ sub-category for the purpose of statistical testing.

The age of the oldest occupant in the household shows a wide spread across all house types. The smallest groups are the dwellings where the oldest occupant is under 30 and over 80, these account for 5% (n=15) and 6% (n=18) of the sample respectively.

The relationship between these (and other) individual descriptors and mean winter temperature will be tested and relationships established. There are also many interesting insights that can be seen at the intersections between two descriptors. The sample is dominated by semi-detached properties; of the 30 house age and house type sub-categories shown here two of these, semi-detached dwellings built between 1920 and 1943 (20%) and between 1944 and 1965 (12%), account for 32% of the sample. The most common intersection between house type and household size is semi-detached properties with 2 occupants (18%). Three of the 35 sub-categories that relate to house type and employment status account of

44% of the sample; semi-detached properties where the HRP is in full time work (21%), mid-terrace where the HRP is in full-time work (10%) and semi-detached properties where the HRP is retired (13%).

The sample described here is large enough to provide a representative insight for each of the descriptors as the sample size of each sub-category, such as mid-terraced properties (60 dwellings) or houses built between 1944-1965 (58 dwellings), are large enough so that any outliers are unlikely to overly influence results. At the intersections between two descriptors, however, for example mid-terraced properties built between 1944 and 1965 (9 dwellings), the sample size of each sub-category are often very small (less than 10) and, therefore, the statistical techniques used in this work would be less robust as they are more discriminating with large sample sizes.

3.3.3 Comparison of sample with 2001 census data and the 2009 English Housing Survey

The Living in Leicester (LIL) temperature sample of 249 homes was compared to data collected during the 2001 census (ONS, 2001) and the 2009 English Housing Survey (EHS, 2009) to examine how representative the sample is of the housing found within both Leicester City and in England as a whole. The LIL survey was undertaken within both the Leicester City Unitary Authority (UA) and data from within this boundary is available from the 2001 census. The process of comparing the sample with data from Leicester and England is essential if the findings of this work are to be applied more widely. If any descriptor is over or under sampled, a weighting can be applied so that results can be scaled to match the composition of housing from that area. A full test of representativeness would be based on the number of dwellings in the sample at the intersections between sub-categories, as the sample size is not large enough for extensive analysis at this level this section will give an insight into how similar the LIL sample is to the other samples only for each descriptor.

The data required for comparison could not be sourced in one place; therefore different descriptors are compared to data collected during the 2001 census and the English Housing Survey 2009. Some of the descriptors relate to different portions of the household and are consequently difficult to compare exactly. For example, employment status data was collected during the 2001 census and is reported for the Leicester UA and England in Table 3-3. In the census, respondents noted the employment status of every household member, while in the LIL Survey details of employment status was only asked of the HRP. This descriptor cannot, therefore, fully indicate how representative the sample is of either the Leicester UA or England as a whole. Other household variables such as house age are not collected in the census and so it has not been possible to gain access to this data at the UA level. House age is compared to data collected during the 2009 English Housing Survey; this data is only available at the national level as it is based on a survey of 22,335 English homes and has not been disaggregated to local authority level. The table gives the percentage of each sub-category in each descriptor found in the LIL survey and in the Leicester and English census samples. It also shows how many percentage points each of the sub-categories difference between the LIL survey and the other two samples. For example, in the house type descriptor semi-detached dwellings account for 46% of the LIL sample, but only 37% of the 2001 census sample taken the in Leicester UA. The number of semi-detached dwellings in the census sample is nine percentage points lower than found in the LIL sample. This reflects the urban nature of the Leicester housing stock and the fact Leicester has a number of large estates which are dominated by semi-detached dwellings.

Table 3-3 Composition of the LIL temperature sample compared to 2001 census data for Leicester Unitary Authority and England and the 2009 English Housing Survey (EHS) showing the percentage of each descriptor and the difference between the LIL temperature sample and the other surveys.

	Percentage in sample				Percentage points difference between LIL temperature sample to other surveys		
	LIL temperature sample (%)	Census Leicester UA (%)	Census England (%)	EHS 2009 (%)	Census Leicester UA	Census England	EHS 2009
House type							
Detached	10	12	23	17	-2	-13	-7
Semi-	46	42	32	25	4	14	21
End terrace	10	41*	26*	11	-7*	8*	-1
Mid terrace	24			19			5
Flat	10	5	19	19	5	-9	-9
Other (bungalow)				9			-9
House age							
pre-1919	18	-	-	21	-	-	-3
1919-44	31	-	-	17	-	-	14
1945-64	23	-	-	20	-	-	3
1965-80	14	-	-	21	-	-	-7
post 1980	13	-	-	21	-	-	-8
Tenure							
Own outright	39	24	29	67*	15	10	3
Buying with mortgage	31	34	39		-3	-8	
Rent	30	40	29	33	-11	0	-4
Household size							
1	26	33	30	-	-6	-4	-
2	37	29	34	-	8	2	-
3	16	15	15	-	1	0	-
4	14	14	13	-	1	1	-
5	4	7	5	-	-3	-1	-
6	2	2	1	-	0	1	-
7	0	1	1	-	-1	0	-
Employment status**							
Full time	42	47	41	-	-5	1	-
Part time	12	4	12	-	8	0	-
Unemployed	6	6	3	-	0	3	-
Permanently unable to work	6	7	5	-	-1	1	-
Look after family	2	2	7	-	0	-5	-
Retired	27	9	14	-	18	13	-
Student	2	13	7	-	-11	-5	-
Other	3	12	11	-	-9	-8	-

*The census data does not break down house type into different types of terrace property

**Data relating to employment status in the census relates to every individual in the home while in this survey employment data was only collected for the HRP

The descriptors that relate to the whole household not individuals in the dwelling are more comparable with the census data. The percentage of detached properties is very similar to the census data found in the Leicester UA. This is partly because the initial sampling strategy stratified for number detached dwellings. This result suggests that there has been little change in the proportion of detached dwellings in Leicester between when the census was collected in 2001 and the living in Leicester survey undertaken in 2009. The proportion of detached dwellings in the sample is much lower than in England as a whole; this is because of there is a high proportion of detached dwelling in rural areas. The number of terraced dwellings is very similar to what was found during the 2001 census in Leicester (the figures for end-terrace and mid-terrace properties were not separated and therefore cannot be compared). Semi-detached properties were over sampled with the LIL sample having 9% points more than the Leicester UA census sample. The number of flats in the sample is under represented compared to the Leicester UA (6% points) and England (10% points). This may be a result of the occupants in flats being younger and less willing to spend time being involved in a lengthy survey.

House age data was not collected during the 2001 census, so the sample can only be compared to England using data from the English Housing Survey 2009. The English housing stock has a higher proportion of houses built between 1945 and 1980 (21% points). The sample has more dwellings built between 1919 and 1944 than the English housing stock (28% points). Dwellings built before 1919 and after 1980 are within 5% points of the English housing stock values.

The LIL temperature sample has a very high proportion of dwellings which are owned outright by the occupants (39%) compared to both Leicester UA (24%) and England (29%). The 2009 EHS did not record whether dwellings were owned out right; house ownership was recorded at 67% compared with 70% in the LIL temperature sample and 58% in the Leicester UA according to the 2001 census.

Household size has the closest fit of all of the descriptors with all of the sub-categories falling within 7% points of the Leicester census sample and 3% points of the England census sample. This may be related to the initial sampling strategy which stratified for number of dependent children which will have a close relationship with household size.

Although the data that relates to employment status is based on different parameters (the HRP in this sample and all household occupants in the census) the number of households with an employment status of full time is similar to the Leicester UA census data (5% points) and the England census data (-1% point). The proportion of HRPs who are in part time employment and retired have been over sampled; these categories are 8% points and 18% points higher, respectively, than the Leicester UA census as a whole. This sampling problem may be related to the availability of these demographic groups to partake in lengthy interviews and suggests some sampling bias.

On the whole the LIL temperature sample is reasonably representative of the Leicester UA census data with the most significant difference being related to tenure. It is unclear from the literature how tenure will impact on indoor temperatures and consequently it is not possible to assess whether the differences in tenure between these samples will reduce the validity of applying results to the Leicester UA. The LIL temperature sample, however, differs from the England census data in the house type descriptor which is expected to have a significant impact on indoor temperatures (this is also reflected by the difference between the Leicester UA and England census data). To apply results from this analysis at the national level, therefore, a weighting system will be required which takes into account the frequencies of dwellings in the house type descriptor in the sample and at the national level.

3.4 Complexity in temperature data

This section shows how people interact with their environment and heating systems and the resulting effects on indoor temperature traces. The aim is to illustrate the complexity of working with data collected in real world settings. Five examples of inconsistent or problematic occupant behaviour are discussed: inconsistent heating where occupants change the way they heat their home on a regular basis; unusual heating patterns (one-off departures from regular heating practices); the use of secondary heating; window opening and; variation in heating control. Each of these will impact on the analysis described in the following results chapters.

3.4.1 Inconsistent heating patterns

The first challenge is inconsistent heating patterns, which occur when household occupants change heating practices over time. As discussed in Chapter 2, building energy models use standard assumptions about how household occupants use their heating systems. In housing stock energy models it is usually assumed that a standard heating schedule is used across all dwellings over the whole heating season.

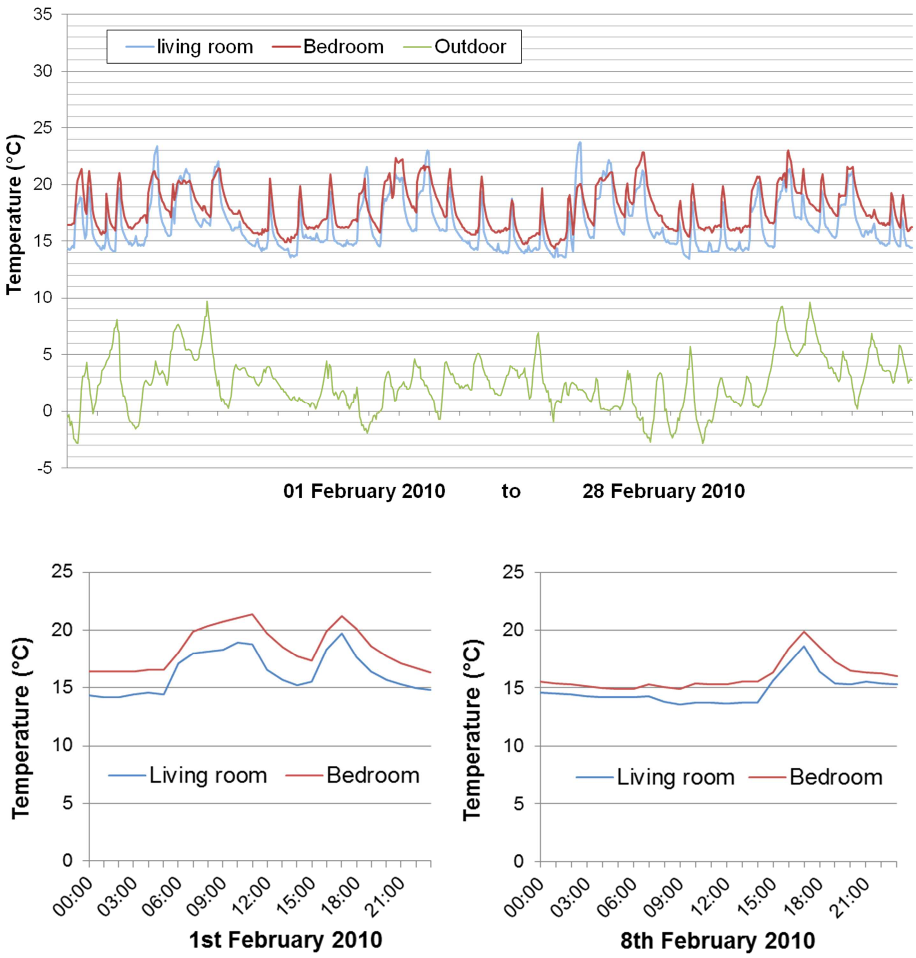


Figure 3-14. Monthly (top) and daily (bottom) temperature plots from a single dwelling showing days where single and double heating patterns are used.

The temperature traces, however, show clearly that heating patterns change significantly over time. Variability in occupant behaviour includes changing between single and double heating patterns (Figure 3-14) and changing thermostat settings or thermostatic radiator values (Figure 3-15). In the dwelling depicted in Figure 3-14 the heating is most often used once a day but on approximately a third of the days a double heating pattern is used (i.e. the dwelling is heated in the morning and in the evening). No clear pattern of when the behaviour changes can be established.

Another heating behaviour in dwellings is changing the thermostat setting (Figure 3-15). In this dwelling a single heating pattern is predominantly used, the living room temperature reaches a peak temperature of over 25℃ each day. On the 20th February the temperature drops in both the living room and bedroom and the diurnal swing in the living room temperature substantially smaller. It is unlikely that this is the result of sensors being moved as there was a step change in the temperature readings of both sensors; on the same day and after the change the sensors were still measuring different temperatures. It is possible that this was a result of the room thermostat being turned down on the 20th February. The heating pattern remains similar throughout the whole month shown (i.e. single heating period each day). It is clear that the average daily temperature and the thermostat setting calculated for each of the two periods (i.e. before and after the change in thermostat setting) will be different.

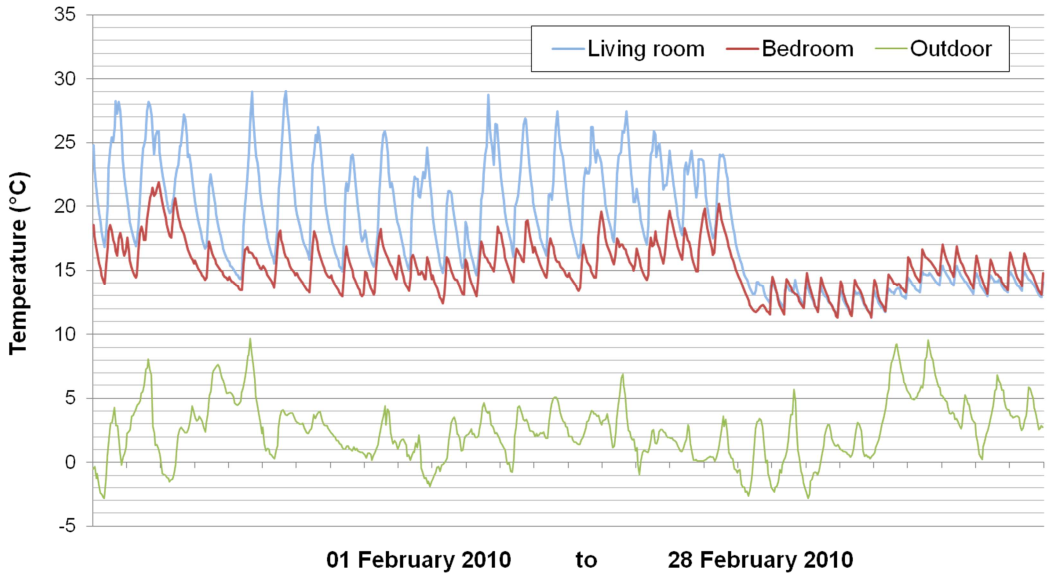


Figure 3-15. Monthly plot for a single dwelling showing a step change in measured temperature.

3.4.2 Unusual heating patterns

The second challenge is unusual heating patterns, which are described as one-off events that differ from the usual heating regime and can be seen when observing monthly temperature traces. These may be related to periods where dwellings are unoccupied or when occupants override their usual heating schedule and exercise manually control.

Figure 3-16 is an example of a dwelling where the occupants changed their heating schedule as a one-off event. Initially a single heating pattern can be observed. On the 13th February the heating controls are overridden and the indoor temperature increases constantly in the living room for three days, rising to a peak temperature of 26.8℃, the bedroom temperature incr eases for two days. At this point the heating is used only for part of the day again and after three days a new regular schedule can be observed. After the one-off incident a slightly higher temperature is maintained and a double heating pattern is used. During this period with the unusual heating pattern, the daily average temperatures are higher than on the other days.

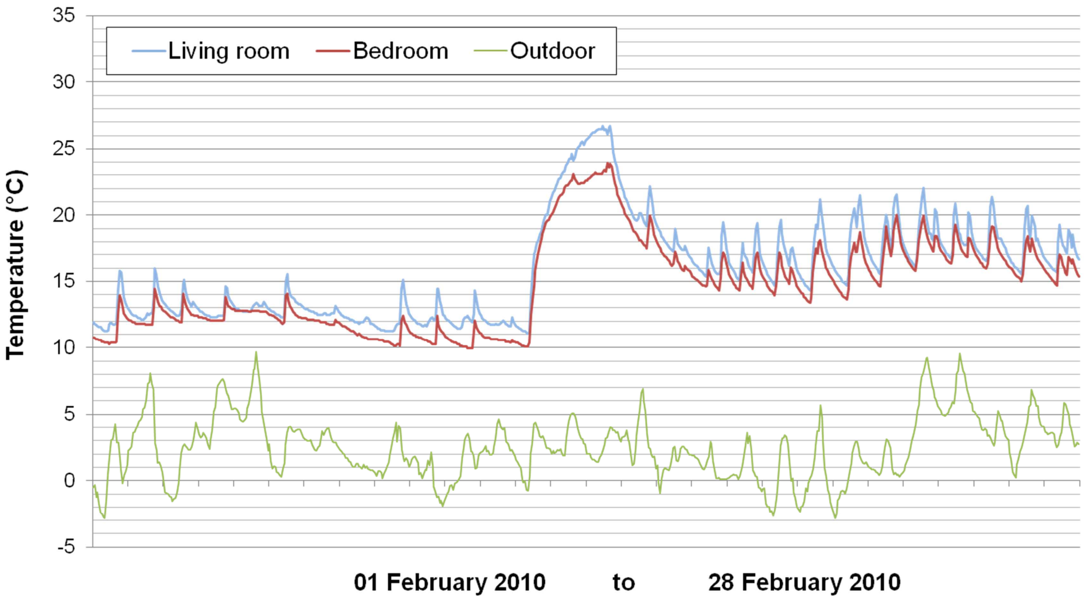


Figure 3-16. Monthly temperature plot from a single dwelling showing heating being left on continuously for a number of days.

As this is an empirical study aiming to understand how dwellings are heated during winter periods households were not excluded as a result of unheated periods. In the example below no heating can be observed, in either room, for the first ten days of February. After this period, when temperatures are consistently low, the indoor temperatures increase in both spaces and are then maintained with a consistent heating pattern where the daily peaks in the living room suggest a thermostat setting of approximately 23℃. As discus sed in reference to the example shown in Figure 3-15, daily temperatures calculated for the two distinct periods will be significantly different.

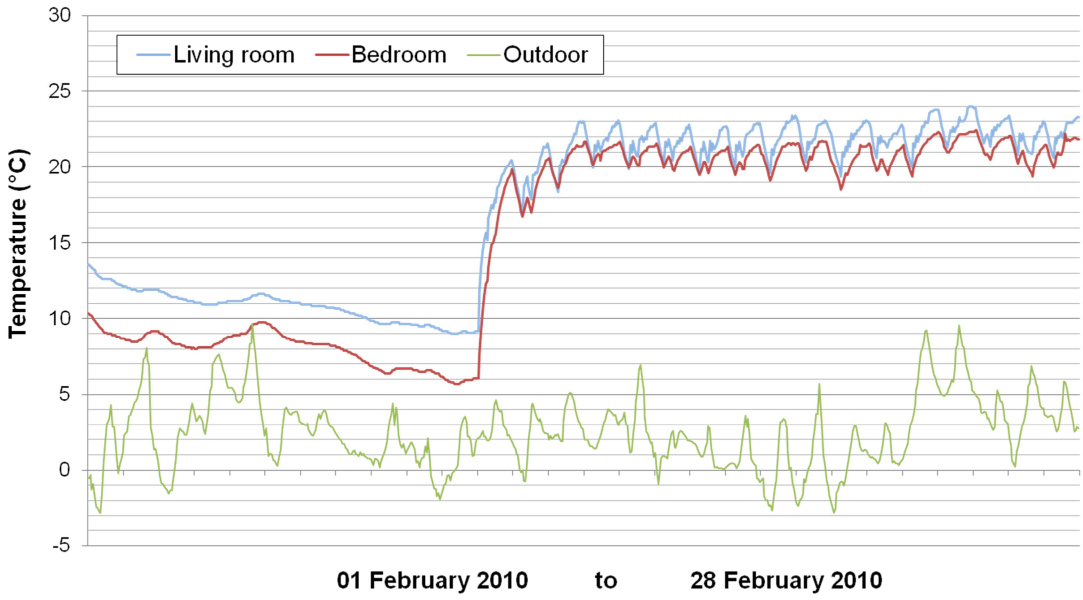


Figure 3-17. Monthly temperature plot for a single dwelling showing an example of an unheated period.

3.4.3 Use of secondary heating

The third challenge is the use of secondary heating which is the first of two specific behaviours which will impact on indoor temperatures but which do not relate to household occupants' use of central heating systems. Over 90% of dwellings in the UK are heated via central heating systems; however, in many of these secondary heating is also used.

The example below shows the temperature change on the 1st February in a single dwelling (Figure 3-18). Temperatures drop overnight in both the living room and the bedroom. In the bedroom the temperature increases between 8:00am and 10:00am, while the temperature in the living room continues to fall, this is likely to be related to the use of a secondary heat source in the bedroom. The temperature starts to increase in both rooms from 2:00pm until a peak temperature is reached in both living room and bedroom spaces at 10:00pm. This is likely to be related to the use of central heating, as both rooms respond, although the temperature in the bedroom dips at 5:00pm which could be related to window opening.

Secondary heating is very flexible and can be moved from room to room and consequently offers a challenge in analysis of temperature data. Secondary heating is also used in response to changes in environment or circumstances and is difficult to capture statistically in a large sample.

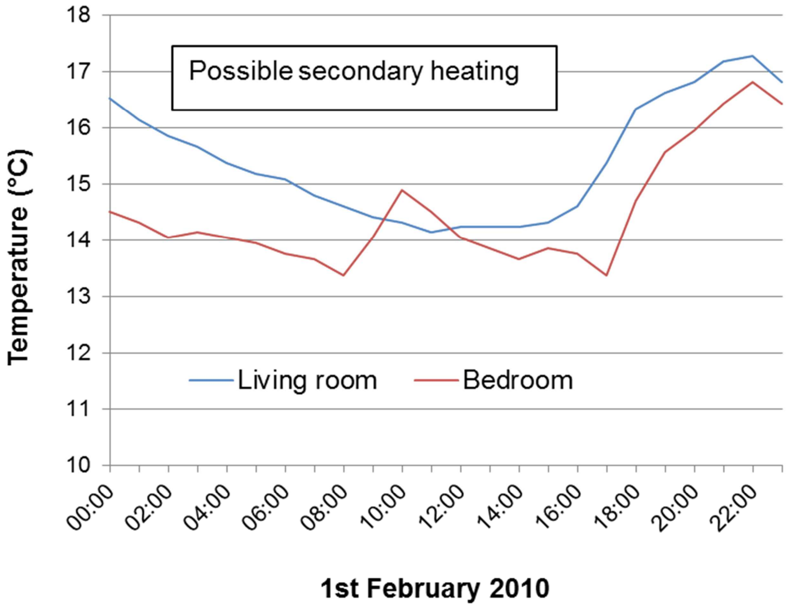


Figure 3-18. Daily temperature plot of a single dwelling possibly indicating the use of secondary and central heating.

3.4.4 Window opening

The fourth challenge is window opening, during winter periods when outdoor air temperatures are lower than indoor temperatures during both heated and unheated periods window opening might be occurring when the temperature drops in one room but the temperature in the other room is maintained or is increasing.

Figure 3-19 shows the indoor temperature measured in a single dwelling on 1st February 2010. Temperatures drop overnight in both rooms, but at 5:00am the heating comes on and temperature increases until 9:00am. The temperatures then fall but start to increase in both rooms again at 10:00am. The temperature increases in the living room until 3:00pm after which it is maintained (an example of successful thermostatic control perhaps). The bedroom temperature, however, decreases quickly (the temperature falls quicker than overnight when the outdoor temperature was lower) suggesting that a window was opened in the bedroom after 12:00am and was closed between 4:00pm and 5:00pm after which the temperature in the bedroom increases until it reaches a peak at 10:00pm when the heating is turned off.

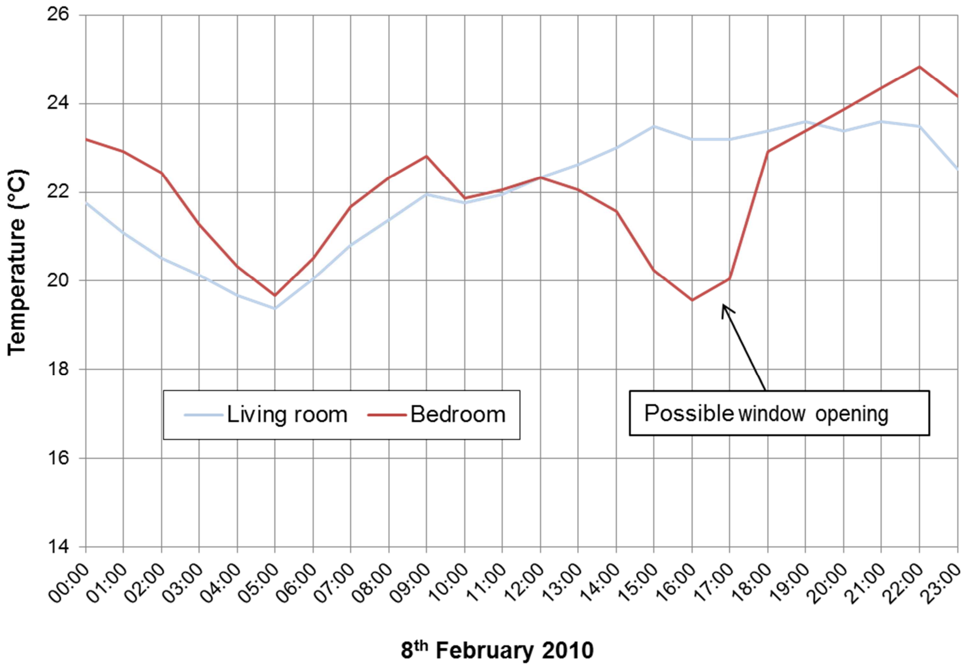


Figure 3-19. Single day plot of indoor temperature in a one dwelling showing possible evidence of window opening.

Instances of window opening will lower daily temperatures but there is no way of knowing whether the room was occupied during these periods.

3.4.5 Variation in heating control

Whether a dwelling has successful thermostatic control will influence the result of the calculation of the heating metrics. Figure 3-20 shows indoor temperature measured on a single day and is a good example of a dwelling with successful thermostatic control. Heating is turned on at 6:00am and is used until 10:00pm. Indoor temperatures rise quickly when the heating is turned until the demand temperature of 24℃ is reached around 11:00am. Afte r this the boiler cycles (turns on and off) to maintain an indoor air temperature of approximately 24℃. When the temperature reaches 24℃ the boiler turns off and t he radiators start to cool down during this process heat is still radiated into the room so the temperature does not drop very quickly. When the radiators are cooler the indoor temperature will drop until the thermostat records a temperature below 24°, at this time the boiler will start to heat the water in the system again and the indoor air temperature will increase. Although most of the households in the sample reported having room thermostats, successful thermostatic control as shown in this example was observed in relatively few dwellings. This is partially related to the fact that the hourly recordings taken during this monitoring are not able to show subtle fluctuations in indoor temperature and therefore thermostatic control can only be observed in dwellings with very long heating periods or those which reach the thermostat setting very quickly i.e. in well insulated dwellings with very responsive heating systems.

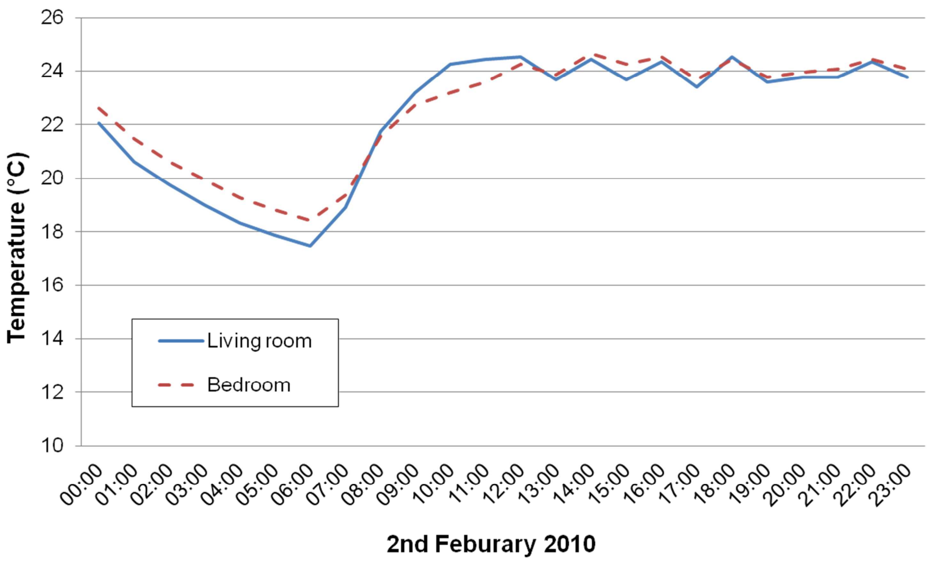


Figure 3-20. Temperature plot of a single day in one dwelling showing a single heating period and successful thermostatic control.

Figure 3-21 shows an example where thermostatic control cannot be observed temperatures increase constantly during the 8 hour heating period, between 01:00pm and 09:00pm, at the time when the temperature starts to drop the peak temperature measured in the living room is 19.0℃. The mean temperature in a dwelling with a similar heating period and thermostat setting that is reached quickly thermostatic control would be higher as the peak temperature is maintained (as in the example above). In reality it might be expected that higher demand temperatures will be observed in dwellings with little or no thermostatic control as the temperature will increase until the heating turns off. Where successful thermostatic control is seen, however, temperatures only increase until the demand temperature is reached and therefore higher temperatures might not be reached.

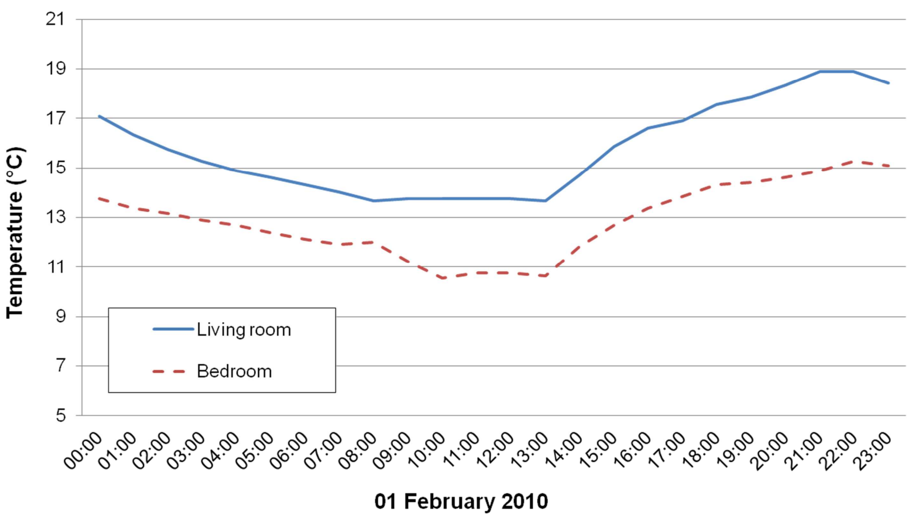


Figure 3-21. Example of temperatures where thermostatic control cannot be observed from the temperature traces measured in on 1st February 2010.

3.5 Statistical analysis techniques

The aim of this work is to show the variation in indoor temperature and heating practices across the housing stock and establish whether this variation is related to social and technical household descriptors. To present this information a number of statistical approaches were required. This section introduces the statistical techniques used, discusses the assumptions which underpin them and shows where they have been used in previous related research.

3.5.1 t-tests

Significance testing measures how reliable the relationship is between independent and dependant variables (Field, 2005). When there are two groups t-tests for two independent samples are used, if three or more groups are present analysis of variance is required. The difference between two sample means is said to be statistically significant when the variance between the data points within each group is small compared to difference in means of the groups.

The t-statistic for differences between two independent sample means (A and B) is calculated by dividing the difference between the two group means by the total standard error as shown below (Equation 3-1).

$$t = \frac{\bar{X}_A - \bar{X}_B}{\sqrt{\frac{S_A^2}{n_A} + \frac{S_B^2}{n_B}}}$$ Equation 3-1

Where $\bar{X}$ is the mean of each group (A and B), n is the sample size of each group and S^2 is the variance of each group.

The variance is calculated using the equation below

$$s^2 = \frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}$$ Equation 3-2

The critical t is the value at which the t-statistic becomes statistically significant and is based upon the number of degrees of freedom (df) given by the following equation.

$$df = (n_A + n_B - 2)$$ Equation 3-3

The calculated t-value (a value between 0 and 1) and the number of degrees of freedom are used to look up the significance level α on a t-distribution. For this work α = 0.05 was used which means for cases where α < 0.05 there is a 95%

chance that the difference in means of the two samples are genuinely different and only a 5% chance that the means are not statistically different.

Testing for statistical significance using t-test makes a number of assumptions about the data.

1) The samples are normally distributed
2) The samples have equal variance
3) Samples are selected at random

t-tests, however are robust and can be applied even in cases where variances differ significantly (McKillup, 2006).

As each time a t-test is used and it is concluded that there is a statistically significant difference between the means of the two groups, as this test is based on a 95% probability each time the test is carried out, there is a 5% chance of an incorrect result. This is called type 1 error and as a result of this error it is not appropriate to use multiple t-tests to test for statistical differences between the means of more than two groups in a sample.

3.5.2 Analysis of variance

Analysis of variance (ANOVA) has been used in energy studies (Guerra-Santin & Itard, 2010) and in temperature studies (French et al., 2007). ANOVA is an established and robust technique for testing for statistical differences between the means of samples when more than two groups are present (Field, 2005). ANOVA is a measure of the variance about the mean within and among the groups within a sample. In other words, ANOVA is a measure of the relative effect of a variable on a distribution in respect of the other effects that are not being tested.

Three types of variance are calculated as part of an ANOVA calculation

1) Within group variance, which is a measure of the error or the variation that is related to other factors not being tested.

2) The among group variance which is a measure of the variation that is related to the effect of the descriptor. This is the distance between the mean of each of the sub-categories and the mean of the whole sample being tested.
3) The total variance which is the combined effects of the first two measures.

As in t-tests, when the within group variance is relatively large compared to the among group variance, the variation the differences in sample means can be described as statistically significant.

ANOVA returns an f-statistic or f-ratio calculated by the following equation (McKillup, 2006).

$$f = \frac{among\ group\ variance}{within\ group\ variance\ (s_{wg}^2)}$$

Equation 3-4

Where within group variance is

$$s_{wg}^2 = \frac{\sum \frac{(X_i - \bar{X})^2}{n-1}}{df_{wg}}$$

Equation 3-5

Where df_{wg} is the degrees of freedom within the groups and is calculated by subtracting from the sample size (N) the number of groups (*k*).

And among group variance is

$$s_{ag}^2 = \frac{\sum_{i=1}^{k} n(\bar{X}_i - \mu)}{k}$$

Equation 3-6

Where μ is the sample mean.

The returned f-statistic is then looked up in a table of f-distributions based on the number of degrees of freedom to find the level of significance. Again a value of α of 0.05 is used and where the significance level is less than 0.05 there is a 95% chance that there is a genuine difference between at least two of the groups.

The same assumptions regarding the sample are required in ANOVA as in t-tests. Again, however, ANOVA is robust enough to overcome these assumptions providing that the sample sizes of the sub-categories are reasonably similar. To ensure this, some of the descriptors where groups have low group sample size were recoded so that the sample sizes of the groups were as similar as possible.

When using ANOVA a significant result ($\alpha < 0.05$) does not indicate whether there are statistically significant differences between the means of all of the groups only that there is a difference between at least two of the groups. For example, if there are 5 groups that relate to different house types and the ANOVA result suggested that there is a statistically significant difference between the sample means, it would not be possible to assume that the relationship holds for differences between all house types. It may be the case that the only statistical differences occur between detached dwellings and flats. When a positive result occurs it is therefore important to establish which groups have difference means using post hoc tests.

3.5.3 Post hoc tests

Post hoc test such as the Tukey statistic (q) is applied after a relationship has been shown to be statistically significant and can identify the groups where a difference in sample means occurs.

$$q = \frac{\bar{X}_A - \bar{X}_B}{SEM}$$

Equation 3-7

And SEM = is the standard error calculated using the follow equation

$$SEM = \frac{\sigma}{\sqrt{n}}$$ Equation 3-8

$Where\ \sigma\ is\ the\ standard\ deviation$

$and\ n\ is\ the\ sample\ size$

The critical value of q depends on the chosen value of α, the number of degrees of freedom and the number of different groups being tested.

The output of Tukey post hoc tests show the differences between all groups that were tested using ANOVA and the significant differences can be observed. Where $q < 0.05$ a statistically significant relationship between the two groups tested is established. When a reliable relationship between dependent and independent variables has been established it is important to understand how strong the association is between the variables. Tests of effect size measure the strength of association between independent and dependent variables.

3.5.4 Effect size

When a statistically significant relationship has been established using the appropriate test, a measure of effect size is a measure of the power or effect of that relationship. When using ANOVA, the calculation of effect size is given by Partial eta squared (η^2). Partial eta^2 is the ratio of variance accounted for by an effect and that effect plus its associated error when using ANOVA and is calculated

$$Partial\ \eta^2 = \frac{s_{ag}^2}{s_{ag}^2 + s_{wg}^2}$$ Equation 3-9

Where S^2_{ag} *= sum of squares of effect*

S^2_{wg} *= sum of squares of the errors*

The Partial eta squared calculation returns a value between 0 and 1 and is an indication of how much variation a single descriptor can have on the dependent value. Effect sizes only give an indication of the relative influence of an independent variable on the dependent variable and as tests are carried out one variable at a time it is not possible to establish the influence of interactions between variables. To model the whole influence of a number of independent variables on the dependent variable and calculate the total amount of variation that can be explained regression analysis is required.

3.5.5 Regression analysis

Regression analysis is a well-established technique used in many fields of research (Miles and Shevlin, 2001). In energy research it has been used to establish the drivers for gas consumption in lower level super output areas across England (Morris et al., 2012). Regression analysis has been used in temperature monitoring studies as a standardisation process when data was collected in different locations and at different times and therefore did not have comparable outdoor temperature conditions (Oreszczyn et al., 2006) (Summerfield et al., 2007).

In a simple regression model with one independent and one dependent variable the method of least squares is used to identify the line of best fit. The correlation co-efficient is a measure of how closely the line of best fit matches the data.

When there is more than one independent variable that relates to the dependent variable multiple regression analysis can be applied and is a method for calculating the variance that is related to a number of independent variables while controlling for the other variables in the model.

The correlation co-efficient (R^2) is given using the following equation

$$R^2 = \frac{model\ sum\ of\ squares\ (SS_M)}{total\ sum\ of\ squares\ (SS_T)}$$

Equation 3-10

The correlation co-efficient (R^2) is a figure between 0 and 1 and is a measure of effect size, or how much of the variation can be explained by the independent variables. For example, a perfect correlation will be 1 while if no correlation is observed a value of 0 will be returned. If R^2 equals 0.37 this means that 37% of the variation in the dependent variable can be explained by the independent variables.

A number of assumptions are associated with multiple regression analysis.

- No perfect multicollinearity (correlation between two input variables)
- Predictors are uncorrelated with external variables
- Residuals (errors) are not correlated
- Errors are normally distributed
- The variables are independent
- The relationships between predictors and the dependent variable are linear

The outcome of multiple regression analysis is a numerical equation which can model the variation of a dependent variable based on a number of independent variables which have been found to be statistically significant when controlled for the other variables.

3.6 Summary

A household survey has been carried out in over 500 dwellings in Leicester. As part of this study temperature sensors were installed in the living room and main bedroom of a sub-set of the dwellings. Temperature sensors were set to log temperature each hour between July 2009 and February 2012, at the end of the monitoring period 321 households returned one or more sensors.

Temperature sensors were accurate to ± 0.5℃ and a placement experiment suggested that no additional error should be expected from sensors where the advice of interviewers was followed.

To ensure the validity of results and conclusions based on the analysis of the temperature data, plots of temperature data for all households were inspected by eye and a number of dwellings were excluded from the analysis. 63 households were excluded for a number of reasons including the sensors were not measuring heated space, sensors placed together, data was missing as sensors stopped working during the monitoring period or sensors were placed in direct sunlight.

The final temperature sample comprises of 249 dwellings. The sample composition according to a number of key social and technical household descriptors is discussed. A number of limitations and errors within the data were identified and an explanation of this process given.

There are a number of challenges related to the analysis of real world temperature data, examples of inconsistent and unusual heating practices, use of secondary heating and window open are described and their impact on analysis suggested. A full analysis of these complexities would require a more detailed monitoring approach including window and occupancy sensors, high resolution gas monitoring and a higher resolution of temperature data. As this work aims to present average indoor temperatures and heating practices across the whole heating period, temperature changes which occur during that time will impact on the results but the inability to quantify them in their own right does not reduce the validity of the analysis or results. It is concluded that quantifying the anomalies described is beyond the scope of this study but that these should be explored in future research.

The statistical analysis techniques used in the following chapters are introduced and examples of their use in previous energy and temperature related research given.

4 Indoor temperatures in Leicester homes

This chapter investigates the effect of the household descriptors on average indoor temperatures. Indoor temperature data collected for a winter period between December 2009 and February 2010 in 249 Leicester homes is introduced. As discussed in Section 2.1 there are a number of determinants of indoor temperatures including outdoor temperature, technical descriptors (house type and heating system), social descriptors (household size and the age of the occupants) and the heating practices that occupants use to maintain comfortable indoor conditions. This chapter describes the variation in indoor temperature across the sample and aims to show how much of the variation in indoor temperatures can be explained by descriptors that are collectable via survey methods.

Section 4.1 describes the calculation of mean winter temperature, which is the average temperature recorded for the period December 2009 – February 2010, and shows how this varies across the sample. Section 4.2 describes the amount of variation in indoor temperature with respect to technical and social descriptors and investigates which are the most important descriptors that are collectable via survey techniques. Section 4.2 uses multiple regression analysis to describe the amount of variation of mean winter temperatures survey descriptors can describe. Section 5.5 summarises the initial result and indicates how important heating practices are in maintaining indoor air temperatures during winter periods.

4.1 Initial results: The variation of mean winter temperatures

During summer periods changes in indoor temperatures in domestic dwellings in the UK are predominantly related to changes in external conditions; the effects of solar radiation and outdoor air temperature. As the outdoor air temperature drops occupants manage the temperature in their dwellings by using their heating systems. As a result of the heating practices used by households outdoor air temperature has less of an overall impact on mean indoor temperature during winter periods. In most dwellings, however, there are periods of time each day when the heating is not in use and during these periods indoor temperatures are still influenced by the outdoor air temperature. To gain an initial insight into the indoor temperatures in the 249 homes mean winter temperature was calculated for each dwelling in the living room and the bedroom.

The aim of this work is to study indoor temperatures during heated periods. The first stage in this analysis is to calculate average temperatures for the period of the winter when most, if not all, dwellings are heated. The method for establishing the start of the heating season is outlined in Chapter 5. It was found that all dwellings in the sample were heated between December 2009 and February 2010 and therefore this was defined as the winter heating period and is used as the reference period for most of the results that follow. The mean winter temperature is the average of all of the hourly temperatures measured during the period 1st December 2009 to 28th February 2010.

Table 4-1. Mean winter temperature measured in 249 dwellings in Leicester between December 2009 and February 2010.

	Mean winter temperature (℃)	
	Living room	Bedroom
Mean temperature	18.5	17.4
Standard deviation	3.0	2.9
Median	18.7	17.7
90th Percentile	21.9	20.7
10th Percentile	14.3	13.7
Maximum	25.7	24.2
Minimum	9.7	7.6

The mean winter temperatures measured in living rooms and bedrooms are 18.5℃ (standard deviation 3.0℃) and 17.4℃ (stand ard deviation 2.9℃) respectively (Table 4-1). These mean winter temperatures are slightly lower than those reported in the previous UK based temperature monitoring studies discussed in section 2.3. This may be because this work is focused on the coldest part of the winter when average outdoor temperature was 2.3℃ which is lower than the 5℃ used as the outdoor air temperature in some earlier temperature monitoring studies which used a standardisation process. The temperatures recorded at the 90th and 10th percentile show that there is a large variation in mean winter temperature and the sample is negatively skewed (skewness is -0.033 and -0.397 for living rooms and bedrooms respectively).

When rounded to one significant figure the median mean winter temperature is 19℃ in the living room and 18℃ in bedroom spaces (Figure 4-1). The highest mean winter temperature was measured in a living room (25.7℃), the lowest in a bedroom (7.6℃). It is expected that the households with mean winter temperatures above the 90th percentile temperature of 21.9℃ (living room) and 20.7℃ (bedroom) heat their homes for long periods of the day, have higher demand temperatures or have low heat loss through the building fabric.

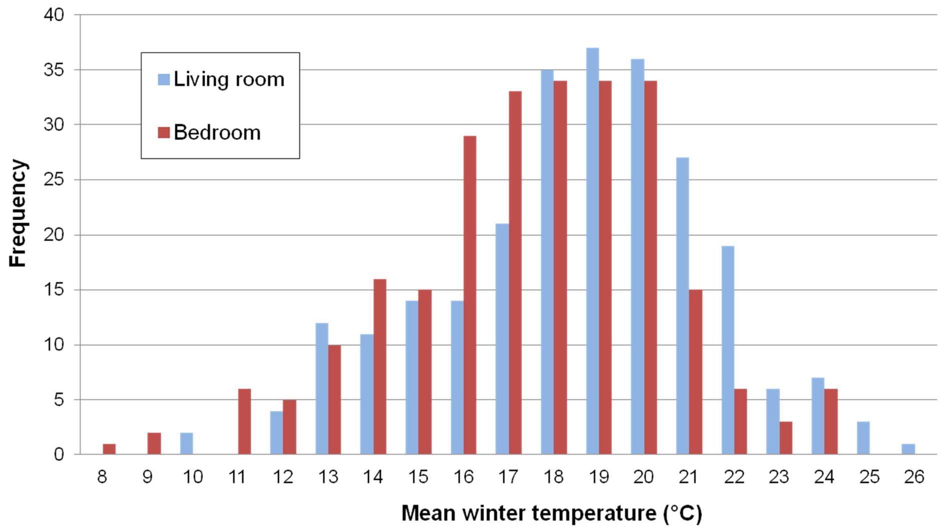


Figure 4-1. Histogram of 249 mean winter temperatures measured between December 2009 and February 2010 for living room and bedroom spaces.

It is expected that households with mean winter temperatures below 16℃ will have low demand temperatures, high heat loss through the building fabric or have long periods where the building is not occupied.

A number of dwellings can be observed with a very low mean winter temperature, the minimum mean temperatures in living rooms and bedrooms were 9.7℃ and 7.6℃ respectively. As all dwellings were checked to ensure that sensors were placed in heated spaces, these cold dwellings are most likely to be the result of low demand temperatures, short heating periods and long periods when the dwellings are not occupied during which heating is not in use.

4.2 Variation in mean winter temperature according to descriptors collected during the Living in Leicester survey

4.2.1 Description of statistical approach

This section identifies the descriptors collected as part of the LIL survey that have the greatest influence on mean winter temperatures. Statistical tests were applied to establish the reliability and strength of relationships between the descriptors and mean winter temperature (Table 4-2). T-tests and analysis of variance (ANOVA) were used to test for statistical significance. Statistically significant differences between one or more of the sub-categories are present when the significance level is below 0.05 ($p<0.05$). In these cases the relationship between mean temperature and the descriptor is significant. When statistically significant relationships were identified post hoc tests were used to ascertain where the differences in sample means of the various sub-categories occurred. For example, in the house type category a statistically significant relationship is identified ($p=0.030$). This means that there is a statistically significant difference between two or more of the house type sub-categories but it does not tell us which ones. As a significant relationship was identified post hoc tests were applied to the data; a statistically significant difference was found between the mean winter temperature measured in mid terraces and flats ($q=0.031$). An example of the output of post hoc tests is shown in Appendix A.2.1. The significance level for the post hoc tests between the sample means of the other house types was greater than 0.05 and are not statistically significant. Partial η^2 was calculated to estimate the effect size so that the strength of the relationship between each descriptor and mean winter temperature could be assessed. To use these statistical methods some of the descriptors required recoding to ensure that there were adequate numbers of dwellings in each of the sub-categories. An explanation of the statistical terms and methods is given in Section 3.5.

Table 4-2. Results of statistical analysis of mean winter temperatures to all household descriptors. Significance testing using t-test and ANOVA and effect size using partial eta squared.

	Living room			Bedroom		
	ANOVA result (F-ratio)	Sig. p (α=0.05)	Effect size (Partial η2)	ANOVA result (F-ratio)	Sig. p (α=0.05)	Effect size (Partial η2)
Employment status	4.633	0.001**	0.071	1.350	0.252	0.022
Reported heating period	2.801	0.006**	0.096	1.975	0.051	0.070
Age of oldest occupant	3.109	0.010**	0.060	0.592	0.706	0.012
Tenure	4.334	0.014**	0.034	0.201	0.818	0.002
House age	2.889	0.015**	0.056	1.679	0.140	0.033
Wall type	3.603	0.029**	0.028	0.489	0.614	0.004
House type	2.727	0.030**	0.043	0.908	0.460	0.015
Household size	2.220	0.067	0.043	2.678	0.032**	0.042
Has conservatory*	1.780	0.183	0.007	2.625	0.106	0.011
Proportion of double glazing	1.414	0.245	0.011	1.299	0.275	0.010
Has thermostat*	0.917	0.339	0.004	0.616	0.433	0.002
Reported thermostat setting	1.112	0.348	0.030	2.814	0.043**	0.072
Boiler type	0.847	0.430	0.007	0.337	0.714	0.003
Central heating or not*	0.265	0.607	0.001	4.117	0.044**	0.016
Income (low medium high)	0.451	0.638	0.004	1.106	0.333	0.009
Education*	0.206	0.650	0.001	2.763	0.098	0.011
Proportion of roof insulation	0.649	0.663	0.013	1.975	0.083	0.039
No of bedrooms	0.525	0.665	0.008	1.331	0.265	0.019
Thermostat position	0.452	0.716	0.006	2.186	0.090	0.026
Number of children below 16	0.407	0.748	0.005	1.437	0.232	0.017

*These descriptors only have two groups and therefore results here are based on t-tests not ANOVA. These two statistics are, however, directly comparable.
**These descriptors are statistically significant

Ten descriptors were found to have a statistically significant relationship with mean winter temperature. Four of these were technical descriptors; house type, house age, central heating or not and wall type. Four of these were social descriptors; employment status, tenure, age of oldest occupant and household size. Two of the descriptors were related to the heating practices that household occupants use to maintain preferred indoor temperatures; reported daily heating period and reported thermostat setting.

4.2.2 Variation in mean winter temperature relating to technical descriptors

In section 4.2 it was demonstrated that ten descriptors have a statistically significant relationship to mean winter temperature. This section seeks to explain why these descriptors are related to mean winter temperatures and to describe the extent of variation within each descriptor and their sub-categories.

House type was expected to influence mean indoor temperatures as a result of differences in the number of exposed walls between dwellings with different built forms (house type is also a rough indicator of floor area). The relationship between house type and mean winter temperature measured in living rooms was found to be statistically significant (p=0.022) but not for bedrooms (p=0.303). Post hoc tests showed that in living rooms there were significant differences between the sample means from both flats and detached dwellings and flats and mid-terraced properties. There was no statistical difference between the mean winter temperature calculated for end-terrace and semi-detached dwellings. Partial η^2 for living rooms relating to house type was 0.043 suggesting only a weak relationship between house type and mean winter temperature exists. The mean winter temperature measured in detached dwellings was 17.8℃ and 17.4℃ in living rooms and bedrooms respectively (Table 4-3). This compares to 20.0℃ and 18.5℃ measured in flats. Mid-terraced properties h ad low mean temperatures in both living rooms (17.9℃) and bedrooms (17.4℃). M ean winter temperatures in semi-detached dwellings was 18.7℃ in living rooms which is higher than both detached and mid-terraced properties but the bedroom temperatures measured in semi-detached dwellings were the coldest of all house types (17.2℃).

As stated above, the only statistically significant difference between the different house types was found between flats and mid-terrace properties, this may explain why the effect size is so small (Partial η^2 = 0.030 & 0.015). These results contradict previous studies which have found that converted flats had the lowest average temperatures (Oreszczyn et al., 2006) (Hunt and Gidman, 1982). This may be a result of their being only a single category for flats in this sample due to the small numbers of flats. Hunt also found that detached dwellings were the warmest, this study however was undertaken when a much lower proportion of dwellings were centrally heated (50% in Hunt's sample).

Table 4-3. Mean winter temperatures measured in 249 dwellings in Leicester between December 2009 to February 2010 showing temperature related to the technical descriptors that have been shown to have a statistically significant relationship with mean winter temperature. Statistically significant differences between mean temperatures are shown in bold.

	N	Mean temperature (℃) (lower and upper 95% confiden ce intervals (℃)) Standard deviation (℃)					
		Living room			Bedroom		
All dwellings	249	18.5	(18.1-18.9)	3.0	17.4	(17.1-17.8)	2.9
House type							
Detached	20	17.8	(16.5-19.1)	3.2	17.4	(16.3-18.6)	2.9
Semi-detached	115	18.7	(18.2-19.2)	2.8	17.2	(16.7-17.8)	3.0
End terrace	26	18.2	(16.8-19.6)	3.3	17.5	(16.0-18.9)	3.4
Mid terrace	62	**17.9**	(17.1-18.6)	2.9	17.4	(16.8-18.1)	2.5
Flats	26	**20.0**	(18.7-21.3)	3.1	18.5	(17.2-19.7)	3.0
House age							
Pre 1900	15	16.9	(15.5-18.2)	2.4	16.4	(15.0-17.7)	2.4
1900-1919	31	17.3	(15.9-18.7)	3.7	16.7	(15.4-18.0)	3.5
1920-1943	77	18.4	(17.7-19.0)	2.8	17.3	(16.7-18.0)	2.9
1944-1965	58	19.0	(18.1-19.8)	3.2	17.4	(16.6-18.2)	3.0
1966-1980	35	19.4	(18.6-20.1)	2.3	18.2	(17.3-19.0)	2.4
Post 1980	33	18.8	(17.8-19.8)	2.8	18.2	(17.2-19.1)	2.7
Wall type							
Solid wall	107	**18.0**	(17.4-18.6)	3.0	17.4	(16.8-17.9)	2.7
Unfilled cavity wall	61	18.4	(17.6-19.3)	3.3	17.3	(16.3-18.2)	3.6
Filled cavity walls	81	**19.2**	(18.6-19.8)	2.7	17.7	(17.1-18.3)	2.7
Central heating							
Yes	232	18.5	(18.1-18.8)	3.0	**17.5**	(17.2-17.9)	2.8
No	17	18.8	(17.4-20.3)	2.9	**16.1**	(14.1-18.1)	3.9

On average, the heat loss from older dwellings is greater than newer buildings it was therefore expected that newer dwellings would have higher mean winter temperatures. The relationship between house age and mean winter temperature was found to be statistically significant in living rooms (p=0.015) but not for bedrooms (p=0.140). However, post hoc tests showed no statistical differences between age ranges were present. This may be a because of the number of sub-categories tested, the most significant relationship was between the 1900 -1919 dwellings and the dwelling built between 1966 and 1980 (q=0.059). This result may have proven significant if there were more dwellings in each house age sub-category as ANOVA is less robust where samples sizes are small or unequal.

The oldest buildings, built before 1900, had the lowest mean winter temperatures of 16.9℃ and 16.4℃ in living rooms and bedrooms. The mean winter temperatures increase in each age band probably as a result of improvements in the thermal efficiency of the building fabric causes by changes to the building standards. This trend continues until the most recent age band. In post 1980 dwellings the mean winter temperature is 18.8℃ which is slightly lower than the previous 1966 to 1980 age range. This may be because thermal comfort is related to air temperature and air movement or draughts (CIBSE, 1999). Newer properties are built to higher air tightness standards and are less draughty. In more air tight properties thermal comfort can consequently be maintained at lower air temperatures.

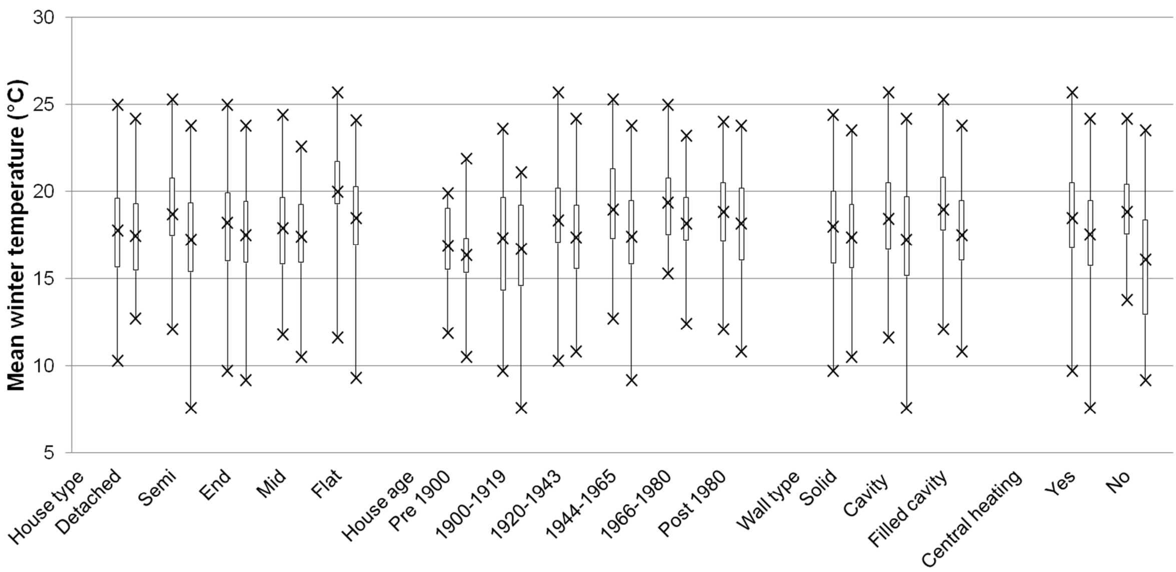


Figure 4-2. Mean winter living room (left) temperature and bedroom (right) according to selected technical descriptors measured in 249 households during December 2009 and February 2010. Showing minimum, 1st quartile, mean, 3rd quartile and maximum mean winter temperature.

Wall type is closely linked to house age as most houses built before 1930 were built using solid wall construction and all dwellings built after 1990 have insulated cavity walls. The relationship between wall type and mean winter temperature was statistically significant ($p=0.029$) for living rooms but not for bedrooms ($p=0.614$). Post hoc tests, however, showed that only the sample means of solid wall and filled cavity groups were statistically different. Partial η^2 for living rooms was 0.028 for the wall type descriptor, however, as wall type and house age are closely related, it is unlikely that these two descriptors when used together could explain much of the variation in mean winter temperature. As expected, solid wall dwellings had the lowest mean winter temperatures 18.0℃ in living rooms and insulated cavity wall dwellings had the highest mean winter temperature of 19.2℃. Mean winter temperature measured in living rooms in dwellings with unfilled cavity walls was 18.4℃.

The descriptor which indicates whether a dwelling has central heating was found to have a statistically significant relationship with mean winter temperature for bedrooms (p=0.044) but not for living rooms (p=0.607). This indicates that in the dwellings which are centrally heated a higher temperature is maintained throughout the dwelling while in dwellings with no central heating, living room temperatures (18.8℃) are maintained with fixed hea t sources, such as gas fires, and are comparable with the temperatures seen in centrally heated dwellings (18.5℃) but bedroom temperatures are considerably lower (centrally heated = 17.5℃, not centrally heated = 16.1℃).

4.2.3 Variation of mean winter temperature relating to social descriptors

This section describes the variation in mean winter temperature according to social descriptors. The technical descriptors discussed above influence the indoor temperature as a result of differences in heat loss through the building envelope. The social descriptors that relate to the household occupants, however, have an impact on when the dwellings are occupied and the type of heating patterns used by the people living in the building.

Table 4-4 Mean winter temperatures measured in 249 dwellings in Leicester between December 2009 to February 2010 showing temperature related to social descriptors that have been shown to have a statistically significant relationship with mean winter temperature. Statistically significant differences between mean temperatures are shown in bold.

		Mean temperature (℃) (lower and upper 95% confidence intervals (℃)) Standard deviation (℃)					
	N	Living room			Bedroom		
All dwellings	249	18.5	(18.1-18.9)	3.0	17.4	(17.1-17.8)	2.9
Tenure							
Own outright	97	18.7	(18.1-19.2)	2.8	17.3	(16.7-18.0)	3.2
Buying with mortgage	78	**17.7**	(17.0-18.4)	3.2	17.4	(16.8-18.0)	2.8
Rent	74	**19.1**	(18.4-19.7)	2.9	17.6	(17.0-18.2)	2.7
Household size							
1	65	17.7	(16.8-18.6)	3.5	**16.6**	(15.6-17.5)	3.7
2	91	19.0	(18.4-19.5)	2.6	**17.9**	(17.4-18.4)	2.6
3	39	18.1	(17.2-19.1)	3.0	17.1	(16.3-17.9)	2.5
4	36	18.9	(18.0-19.8)	2.7	17.8	(17.0-18.7)	2.6
5+	18	18.7	(17.2-20.1)	2.9	18.2	(16.9-19.4)	2.5
Employment status							
Employed	133	**17.9**	(17.4-18.4)	2.9	17.5	(17.0-17.9)	2.7
Retired	68	19.0	(18.3-19.7)	3.0	17.1	(16.3-18.0)	3.5
Unable to work	21	**20.6**	(19.4-21.8)	2.6	18.6	(17.3-19.9)	2.8
Unemployed	15	17.9	(16.3-19.6)	2.9	16.7	(15.5-17.9)	2.2
Other	12	18.9	(17.2-20.5)	2.6	17.8	(16.7-18.9)	1.7
Age of oldest occupant							
20-29	12	**16.4**	(14.2-18.6)	3.4	16.4	(14.3-18.6)	3.4
30-39	41	18.3	(17.4-19.2)	2.8	17.7	(17.0-18.4)	2.2
40-49	59	18.0	(17.3-18.8)	2.9	17.5	(16.8-18.2)	2.7
50-59	39	18.1	(17.1-19.1)	3.1	17.2	(16.2-18.1)	2.9
60-69	50	**19.3**	(18.6-20.1)	2.6	17.8	(16.9-18.7)	3.1
70+	48	**19.2**	(18.3-20.1)	3.2	17.2	(16.2-18.3)	3.5

Employment status was expected to affect how long a dwelling was occupied each day and consequently mean winter temperatures. For example, retired occupants were expected to have longer daily heating periods than those in full time employment. For living rooms employment status produced the most significant result (p=0.001) and is therefore influential in determining the mean winter temperature. Post hoc tests showed, however, that the only statistically significant differences occurred between the means of the employed group and those who were permanently unable to work (q=0.001). Partial η^2 was 0.071 which indicates a weak relationship between employment status and mean winter temperature. This was the largest effect size in any of the technical or social descriptors. No statistically significant relationship was found for bedrooms (p=0.252). Employment status as described here is a relatively poor indicator of the social make up of a dwelling as it only relates to one individual in the dwelling. It is likely therefore, that the effect size relating to a more comprehensive understanding of the employment of household residents or for how long the dwelling is occupied for each day would be larger.

Households where the household representative person (HRP) is employed or unemployed have the lowest mean winter temperatures in living rooms (17.9℃). In bedrooms the lowest temperatures are seen in the unemployed group (16.7℃) (Table 4-4). The mean winter living room temperature in dwellings where the HRP is permanently unable to work is the highest (20.6°C). This difference is probably related to longer heating periods used by households as a result of occupants being present in the dwelling during the day. The mean winter temperature in dwellings where the HRP is retired were 19.0℃ and 17.1℃ for living rooms and bedrooms respectively these temperatures are slightly lower than those where the age of the oldest occupant is over 60 but within the confidence interval. The variation in the difference between maximum and minimum mean winter temperatures is very large in the employment status descriptor (Figure 4-3). The difference ranging between 15.3℃ where the HRP was retired and only 9.6℃ in the ‘other’ sub-category. This result may be partially related to the sample size of the two sub-categories n=68 and n=12 respectively, however the difference between maximum and minimum mean winter temperatures in dwellings where the HRP is employed was 13.9℃ and n=133 for this g roup.

Household size was expected to influence mean winter temperature as dwellings with fewer occupants were expected to have shorter daily heating periods. Household size was the only social descriptor where a statistically significant relationship between mean winter temperature measured in bedrooms was found (p=0.032). This may be a result of increased occupancy of bedrooms in dwellings with large household sizes. A statistically significant relationship was not found in living rooms (p=0.067), but the effect size related to household size (Partial η^2 = 0.043 & 0.042) and was greater than wall type (Partial η^2 = 0.028 & 0.004) where a statistically significant relationship was established. This may be related to the number of sub-categories within the household size descriptor, compared to wall type with only three groups. As there are five household size sub-categories each group has a smaller sample size and high number of degrees of freedom. Post hoc tests showed a significant relationship between the sub-groups with households with one and two occupants in bedrooms (q=0.035) but not living rooms (q=0.055).

Dwellings with the fewest occupants have the lowest temperatures; those with a single occupant have mean winter temperatures of 17.7℃ in living rooms and 16.6℃ in bedrooms. It was expected that mean indoor temperatures would increase with more people living in the dwelling, however, the sub-category where household size was five or more had a mean winter living room temperature of 18.7℃ which is lower than the 18.9℃ that was measured in houses with four occupants. The confidence interval that relates to the mean winter temperature in households with five or more occupants, however, is greater than the other categories in the household size descriptor. This is because as the standard deviation is large and the sample size is small and suggests that this may not be a significant trend. In dwellings with only one occupant the difference between maximum and minimum temperatures is large in both living room (15.9℃) and bedroom spaces (16.7℃). Dwellings with five or more occupants have a smaller range in living rooms (10.1℃) and bedrooms (7.9℃) . The reduced range between highest and lowest mean winter temperatures (variance) across the household size descriptor especially in bedrooms may explain why a statistically significant relationship was shown.

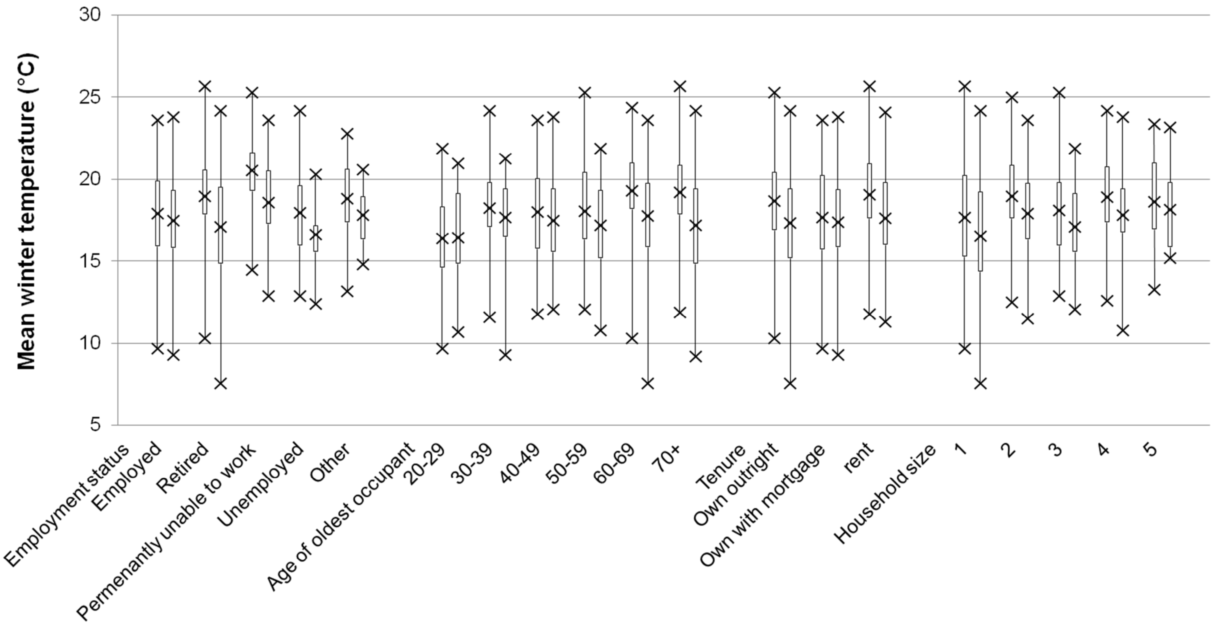


Figure 4-3 Mean winter living room (left) and bedroom (right) temperature according to selected social descriptors measured in 249 households during December 2009 and February 2010. Showing minimum, 1st quartile, mean, 3rd quartile and maximum mean winter temperature.

The relationship between mean winter temperature in living rooms and tenure was found to be statistically significant (p=0.014). Post hoc tests show that this relationship holds between those dwellings that are rented and where occupants are buying their home with a mortgage (q=0.014). The differences in sample means between dwellings where occupants own outright and own with a mortgage are not statistically different. This result is contrary to the expectations described previously as rented dwellings have higher mean winter temperatures than those owned with the help of a mortgage. This may be due to the type of rented dwellings in the sample. Local authority dwellings or those owned by the housing association have often been refurbished and energy improvements made while private landlords have no incentive to make improvements to the energy efficiency of their properties (Druckman & Jackson, 2008). Occupants who are buying their home with the help of a mortgage may have less expendable income and may therefore choose lower demand temperatures; they may also not be able to afford energy improvements. The high number of dwellings that are owned outright in this study may be related to the high number of retired participants and this may also explain the high mean winter temperatures measured in dwellings which are owned outright. In the tenure descriptor mean winter temperatures were 18.7℃ in dwellings that were owned outright and 19.1℃ in rented dwellings. The lowest mean temperatures were measured in dwellings where occupants owned the dwelling with a mortgage (17.7℃). The difference in mean winter temperature in bedrooms between the three groups was only 0.3℃ and therefore no statistical difference was observed (p=0.818). The effect size that relates to the impact of tenure on mean winter temperature measured in living room (Partial $\eta^2 = 0.034$) and bedroom (Partial $\eta^2 = 0.002$) temperatures which shows that only a weak relationship exists.

The relationship between mean winter temperature and age of the oldest occupant was found to be statistically significant for living rooms (p=0.010) but not for bedrooms (p=0.706). Age of oldest occupant has the second largest effect size relating to mean winter temperatures measured in living room spaces (partial $\eta^2 = 0.060$). Households where the oldest occupant is in their twenties had a very low mean winter temperatures in both living rooms (16.4℃) and bedrooms (16.4℃). This differs from anecdotal thought that has assumed that young people demanded high indoor temperatures. Temperatures in both living rooms and bedrooms increase as the oldest occupant in the dwelling gets older apart from the 30 – 40 range which is higher than the 40 – 50 range. This may be related to the presence of children under 5 in these properties; however, there is no evidence that households with children have higher living room temperatures. The highest mean winter temperatures in this descriptor were 19.3℃ and 17.8℃ measured in dwellings where the oldest occupant is between 60 and 69

4.2.4 Variation of mean winter temperature relating to reported heating practices

Two descriptors which relate to heating practices were collected during the LIL survey, reported thermostat setting and reported daily heating period. Reported daily heating period was found to have a statistically significant relationship with mean winter temperatures measured in living rooms (p=0.006) and the relationship in bedrooms was nearly significant (p=0.051). The effect size that relates to reported daily heating period was larger than any of the other technical and social descriptors and suggest that reported daily heating period has a greater influence on mean winter temperature than the technical and social descriptors previously tested (Partial η^2 = 0.096 and 0.070). The fact that reported heating period was found to be related to mean winter temperatures is not surprising as the use of the heating system directly influences indoor temperatures. Reported thermostat setting was not found to have a statistically significant relationship (p=0.348 & p=0.433). This is surprising as thermostat setting should directly influence indoor temperatures. This suggests that occupants do not know what temperatures their thermostats are set to or that thermostats do not have a dominant impact on mean indoor temperatures. This may be because they are poorly placed and therefore they are not working as designed. When a thermostat is placed incorrectly, i.e. in a unheated hallway, an occupant may choose a thermostat setting of 17℃ but as the hallway is not heated the living room temperature where the occupants are present may reach a much higher temperature which is unrelated to the 'thermostat setting'; in this example the thermostat setting value of 17℃ is meaningless and bears no relationship with the temperature which the occupants are attempting to control.

4.3 Multiple regression modelling

Multiple regression analysis was used to identify the amount of variation in mean winter temperature that can be explained by survey data. In the previous section the descriptors which influence mean winter temperature have been identified using statistical methods which assess the impact of a single descriptor on indoor temperature. These statistics, however, are unable to quantify the variation in mean indoor temperatures that can be predicted by descriptors collected via survey techniques as some of the descriptors explain the same variation (as discussed previously regarding the house age and wall type descriptors). As few descriptors were found to be statistically significant for bedrooms only mean winter temperatures measured in living rooms were used in this part of the analysis.

To build a model which included all of the interactions between descriptors a linear regression technique was used. The statistics package SPSS was used to aid this analysis. Initially, as the survey data was categorical (i.e. detached, semi-detached etc.) dummy variables were established for each of the descriptors. Using this method each individual group is entered into the model in binary, so each group is either on or off (Table 4-5). A description of multiple linear regression analysis and its associated assumptions are described in chapter 3.

Table 4-5. Example of dummy coding used for initial regression model showing house type descriptor where the base case is semi-detached.

House number	Detached	End terrace	Mid terrace	Flat
1	0	0	1	0
2	0	0	1	0
3	0	0	0	1
4	0	0	1	0
5	0	0	0	1
6	1	0	0	0

A stepwise entry method was used by which each variable was entered into the model automatically by SPSS if it was statistically significant. A model which included six of the dummy variables was established. The model was found to be statistically significant ($p<0.001$) with an adjusted R^2 of 0.241, which suggests the model can explain 24% of the variation in mean winter temperature in living rooms.

As not all dwellings reported a thermostat setting or heating period, the model is based on a reduced data set of 97 dwellings which includes only households where complete datasets were available.

Table 4-6. Results of multiple regression analysis (categorical approach) used to predict the variation in mean winter temperature measured in 97 living rooms in Leicester.

	B	Standardised coefficient (Beta)	t	Sig.
Constant	17.792	-	54.642	.000
House age 1900-1919	-2.040	-.203	-2.358	.020
Unable to work	2.227	.221	2.602	.011
Reported heating period (under 5 hours)	.075	.148	2.292	.023
Reported heating period (13 - 16 hours)	.014	.143	2.265	.025
Reported thermostat setting (21-22℃)	1.295	.179	2. 099	.038
Reported thermostat setting (23-24℃)	3.620	.261	2. 924	.004

The results of the categorical multiple regression analysis are shown in Table 4-6. The six dummy variables in the model – house age (1900-1919), unable to work, reported heating period (under five hours), reported heating period (13-16 hours), reported thermostat setting (21-22℃) and reported thermostat setting (23-24℃). Each individual Beta value indicates how much the dependent variable (mean winter temperature) will change per standard deviation increase in the predictor variable if the other predictors are kept constant.

To ensure the validity of the regression model a number of tests were applied to the data. Descriptors were tested for multicollinearity (descriptors that correlate too highly with each other). None of the descriptors in the final model were overly correlated (R>0.9) and were therefore acceptable in the model as independent variables. Residual plots were observed for signs of heteroscedasticity the residuals were scattered randomly confirming that the errors are not correlated and the assumptions were not broken.

The B values are used in the regression equation and the model can be expressed show below as:

Equation 4-1

$$Mean\ winter\ temperature\ (living\ room)$$
$$= House\ age\ (1900-1919)\ \times\ -2.040 + Unable\ to\ work\ \times 2.227$$
$$+\ Reported\ heating\ period\ (under\ 5\ hours) \times 0.075$$
$$+ Reported\ heating\ period\ (13-16\ hours) \times 0.014$$
$$+ Reported\ thermostat\ setting\ (23-24°C)\ \times 3.62$$
$$+ Reported\ thermostat\ setting\ (21-22°C)\ \times\ 1.295 + 17.792$$

$$Mean\ winter\ temperature\ (living\ room)$$
$$= 0\ \times\ -2.040 + 1\ \times 2.227 +\ 0 \times 0.075 + 0 \times 0.014 + 0\ \times 3.62$$
$$+ 1\ \times\ 1.295 + 17.792$$

$$= 0 + 2.227 +\ 0 + 0 + 0 + 1\ \times\ 1.295 + 17.792$$

$$= 21.3°C$$

As this is a categorical model each item in the regression equation is either 0 or 1. For example, if a dwelling was built in 1980, had an HRP who was unable to work, was heated for 9 hours per day and had a thermostat setting of 21℃.

The predicted mean winter living room temperature was calculated for all 97 dwellings in the sub-sample and the results compared to the corresponding measured mean winter temperature (Figure 4-4). The limitations of the model can be seen clearly. It predicts, of course, a set of discrete possible mean temperatures, each one defined by a particular set of 0/1 entries in the regression equation. This results in the lines of data points shown in Figure 4-4 because there are limited options in the categorical data, i.e. a house was either built after 1980 or not. The measured values range by up to 15℃ however for some of these predictions.

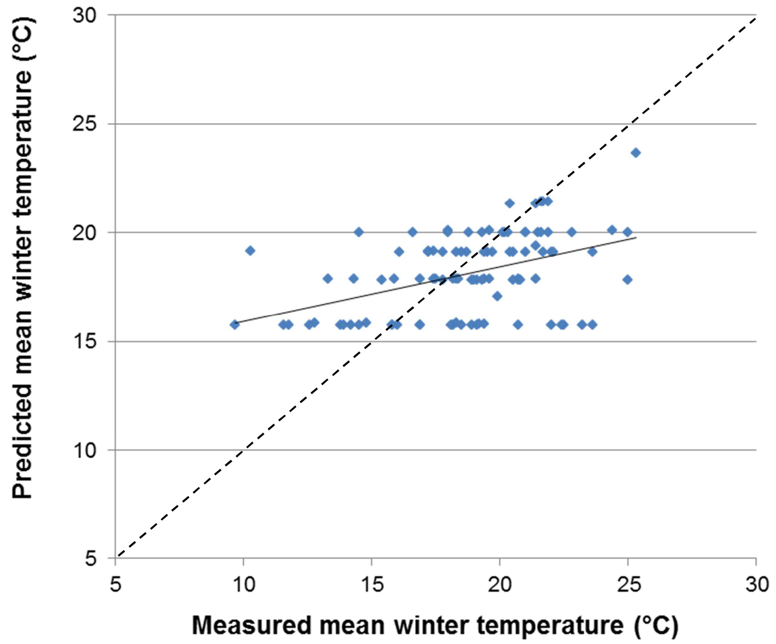


Figure 4-4 Predicted mean winter living room temperature against measured mean winter living room temperature in 97 dwellings in Leicester.

As the model was based on a reduced data set and could not predict mean winter temperatures on a continuous scale a more traditional approach to multiple regression analysis was used. The categorical data such as house age and age of oldest occupant were used in the model as continuous variables where possible. Categorical descriptors such as house type were either split into dummy variables or, where possible, new scales were derived. For example, to recode the wall type descriptor from categorical items to a numerical scale, average U-values for each wall type were chosen based on recommendations in the BREDEM literature (Anderson et al. 2002); Solid wall (2.1), cavity wall (1.6) and filled cavity wall (0.45).

As before, a stepwise method was used and variables were automatically entered into the model if they were statistically significant.

Table 4-7. Results of multiple regression analysis used to predict the variation in mean temperature measured in 97 living rooms in Leicester.

	B	Standardised coefficient (Beta)	t	Sig.
Constant	-11.766	-	-.976	.330
Age of oldest occupant (years)	.037	.203	3.172	.002
Unable to work*	2.284	.205	3.230	.001
Reported heating period	.075	.148	2.292	.023
House age (year built)	.014	.143	2.265	.025

*Categorical variable

The final model includes reported heating period, HRP unable to work, the age of the oldest occupant and the house age (all other variables were excluded as they were not statistically significant) (Table 4-7). The model explains 14% of the variation in mean winter temperature (Adjusted R^2 = 0.144) and ANOVA showed the model to be statistically significant ($p<0.000$). Each individual Beta value expresses the change in the dependent variable (mean winter temperature) will change per standard deviation increase in the predictor variable if the other predictors are kept constant. As before the assumptions required in multiple regression analysis were tested and it was found that they were not violated; the plots and tables which evidence this are shown in appendix A.2.3.

The B values are used in the regression equation and the model can be expressed as below in Equation 4-2. As the employment status descriptor could not be recoded into a continuous variable it was entered into the model as shown previously using dummy variables. The base case for this equation is that the HRP is employed. If a HPR who is employed, is the oldest occupant at 43 years old and lives in detached dwelling built in 1965 the equation which is heated for 4 hours a day becomes the following.

Equation 4-2

$$Mean\ winter\ temperature\ (Living\ room) = 0.037\ \times Age\ of\ oldest\ occupant\ + 0.075 \times Reported\ heating\ period + 2.284 \times Unable\ to\ work + 0.014 \times House\ age - 11.766$$

$$Mean\ winter\ temperature\ (Living\ room) = 0.037\ \times 43 + 0.075\ \times 4 + 2.284 \times 0 + 0.014 \times 1965 - 11.766$$

$$= 01.746 + 0 + 0.300 + 27.647 - 11.766$$

$$= 17.9°\text{C}$$

The average predicted mean winter temperature (18.4℃, standard deviation 1.2℃) and average measured mean winter temperature (18.4℃, standard deviation 2.9℃) are the same, however, the scatter of measured mean winter temperatures is very large ($R^2 = 0.16$).

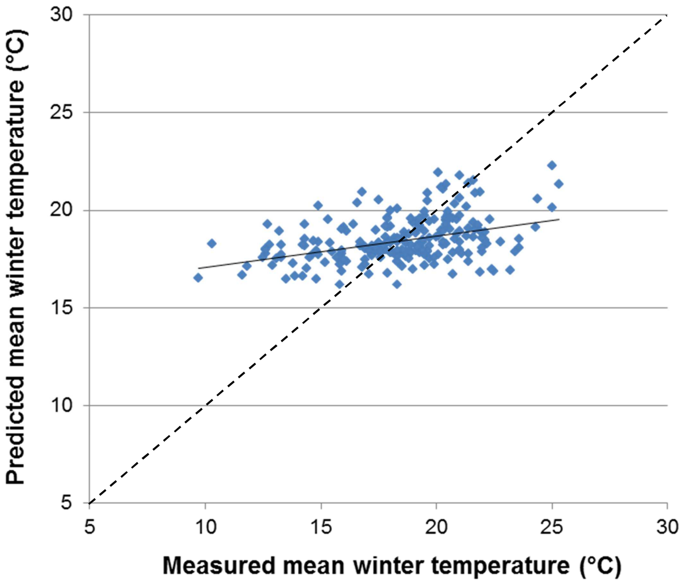


Figure 4-5. Predicted mean winter temperature against measured mean winter temperature in 220 dwellings which provided reported heating periods.

Although only a limited number of descriptors were in the final model this does not mean that these descriptors do not influence indoor temperature, rather the error in the model, which is related to the variation in indoor temperature about each regression line, is larger than the variation in mean winter temperature that the individual descriptor can explain when all other descriptors are controlled.

It is noted that both models under-predict the mean winter temperature in dwellings with high mean winter temperatures and over predict the indoor temperature in dwellings with low mean winter temperatures.

Neither of the models presented here are successful and although the second model can provide continuous temperature predictions the first model accounts for more of the variation in mean winter temperatures.

The model developed by Kelly et al (2013) was found to be able to predict 45% of the variation in indoor temperature between dwellings; however, this model also incorporated data from summer periods which are generally free running, i.e. no additional heating or cooling is required and consequently the large variation in occupant heating practices is less significant

4.4 Summary

Mean winter temperatures (December – February) have been calculated to gain an initial insight into how indoor temperature varies in dwellings in relation to a number of technical and social descriptors.

Mean winter temperatures were calculated for the living room and bedroom in each of the 249 dwellings. Statistical testing was used to identify which descriptors, from those collected during the Living in Leicester survey, had a statistically significant relationship with mean winter temperature. Four technical descriptors (house type, house age, wall type and central heating or not) and four social descriptors (tenure, employment status, household size and age of oldest occupant) were shown to have statistically significant relationship with mean winter living room temperatures. The reported heating practices were also shown to have a statistically significant relationship with mean winter temperatures measured in living rooms. Only household size and whether a dwelling had central heating or not were found to have a statistically significant relationship with mean winter temperature measured in bedrooms. This may be a result of the level of temperature control in living room spaces being greater than in bedrooms, because some households use secondary heat sources to provide extra heat in living room spaces and thermostats are more likely to be placed downstairs near living rooms. A large variation in mean winter temperature was observed within the groups for all of the technical and social descriptors where statistically significant relationships were identified.

The effect size that relates to the seven social and technical descriptors that have been shown to have a statistically significant relationship with mean winter temperature in living rooms, were small and only accounted for a small amount of the variation in mean winter temperatures. When taking into account that some of the variation that the different descriptors is describing is the same, for example the house age and wall type both describe changes to the heat loss through walls, the amount of variation in mean winter temperature that the technical and social descriptors can describe is very small.

Multiple linear regression analysis was undertaken to ascertain the amount of variation in mean winter living room temperatures that the statistically significant descriptors could explain. Two models were built and were found to be statistically significant. The first model could, however, only explain 24% of the variation of mean winter living room temperature. Consequently, it is suggested that it is not possible to predict indoor temperatures using survey data alone. This is most likely related to the variation in heating practices that occupants use to control indoor temperatures during the winter. A deeper exploration of the heating practices used in domestic dwellings is therefore required.

5 Heating practices - timing

The final two results chapters concentrate on the heating practices used by household occupants to control indoor temperatures. Heating practices can broadly be divided into two categories; those that are related to the timing of heating systems (when they are in use and when they are not); and those that relate to the temperatures which are delivered by the heating systems.

This work aims to gain insight into the variation of heating practices across households and therefore average heating practices are reported; average heating practices across winter periods also allows for the results to be compared to model assumptions. Further work into how individual households vary heating practices over time is required.

This chapter describes the timing related heating practices that household occupants use to control indoor temperatures in 249 dwellings in Leicester. The temperature related heating practices are described the chapter 6. Five heating practice metrics are calculated which aim to describe when household occupants heat their homes. Each metric is defined, the reason why it is important discussed, the calculation method shown and results given. The five heating practice metrics discussed in this chapter are:

Table 5-1. Definitions of the heating practice metrics introduced in Chapter 5

	Heating practice metric	Section	Definition
1)	Start of the heating season	5.1	The date in autumn after which household occupants regularly heat their homes
2)	Heating pattern	5.4	The number of times per day which heating is predominantly used
3)	Start and end times of heating	5.5	The first and last times in the day when heat is regularly delivered by the heating system
4)	Daily heating period	5.2	The average number of hours that heating is used per day during the heating season
5)	Number of under heated days	5.3	The number of days during the heating season which are heated with shorter heating periods than is generally used

Section 5.6 describes the main findings of the chapter and shows how the heating practice metrics relate to a number of technical and social household descriptors.

5.1 Heating practice metric 1 – Start of heating season

5.1.1 Calculating start of the heating season

The start of the heating season is defined as the date after which heating is regularly used in a dwelling. The start date of the heating season was determined for two reasons. First, it was important when exploring the other heating practices to base the calculations on the period when heating was used across the whole sample and second, to gain insight into how long the heating season is in different households as this will impact on energy use. A longer heating season will lead to higher energy use.

As the monitoring period (July 2009 to February 2010) did not cover the end of the heating season it was not possible to assess the total length of the heating season. Finding the date that the heating period starts is a challenge as increases in indoor temperature can be related to outdoor temperature, solar and internal heat gains as well as heating. It was, therefore, important to identify when temperature increases were related to heating rather than to other factors. A number of approaches to investigate this were tested. Each method was based only on data measured in living rooms as it was assumed that the temperature would be more carefully controlled than in bedrooms as room thermostats tend to be placed downstairs (118 of the 249 households reported a thermostat position and of these 113 were downstairs).

Three methods were trialled but the start date of the heating season could not be identified successfully using these methods. The first method involved identifying the number of hours per day for which the temperature increased in each dwelling. It was thought that when the heating began a step change would be visible on the plots produced for each dwelling. It was not, however, possible to consistently identify the start of the heating season using this method.

The second method was based on the assumption that any increase in indoor temperature greater than the increase in outside air temperature was related to heating. The difference between the rate of change of indoor temperature and the rate of change of outdoor air temperature and was therefore calculated at each hour. The number of hours per day when the rate of change of indoor temperature was greater than the rate of change of outdoor temperature was calculated for each day. This was then plotted for each dwelling and any trends were identified by visual inspection. This method showed some promise but it was not possible to clearly recognise when occupants started to heat their homes.

The third method used was based on the difference between outdoor and indoor temperature (ΔT). ΔT was calculated for each hour and mean ΔT was determined for each day. As before charts were plotted for each dwelling and visual inspection was used to identify the start of the heating season. It was observed that daily indoor temperature fluctuated far less than outdoor air temperature and therefore many of the plots only showed changes in daily outdoor air temperature and consequently could not be used to identify the start of the heating season. (For further details of the three unsuccessful methods see Appendix A.1.3, A.1.4 & A.1.5)

A fourth method was carried out which was based on the expectation that in each dwelling there is an unheated (summer) period where average daily temperature will be more affected by changes in outdoor temperature than the heated period where average daily indoor temperature will be more consistent. Scatter plots of daily indoor temperature against daily outside temperature were plotted for each dwelling to assess this expectation.

Some scatter or noise was observed, so the plots were drawn again using a running mean temperature as a proxy for daily outdoor temperature. This method has been used previously in summertime temperature monitoring studies to take into account the effect of thermal mass (Wright et al., 2005). The running mean of outdoor air temperature (running mean temperature) also accounts for the adaptive nature of household occupants to outdoor air temperatures, for example the ability of occupants to wear warmer clothing when temperatures fall. The running mean temperature was calculated using the method described in the British Standard BSEN:15251 as shown in the equation below (British Standards, 2007).

$$T_{rm} = (1 - \alpha)(T_{ed-1} + \alpha T_{ed-2} + \alpha T_{ed-3} \ldots)$$ [Equation 5-1]

Where

T_{rm} = running mean of outside air temperature (°C)

T_{ed-1} = mean tempeature of the previous day (°C)

T_{ed-2} = mean tempeature two days ago (°C)

T_{ed-n} = mean tempeature n days ago (°C)

α = constant

The method for calculating the running mean temperature can differ depending on the value of the constant α. As a variant of Equation 5-1 the running mean temperature (T_{rm}) can be calculated using the average temperature of the current day (T_{ed}) as shown below:

$$T_{rm} = (1 - \alpha)(T_{ed} + \alpha T_{ed-1} + \alpha T_{ed-2} \ldots)$$ [Equation 5-2]

Graphs were re-plotted using running mean temperatures calculated using alpha values ranging between 0.8 and 0.2 and based on Equations 5-1 and 5-2 (Figure 5-1). In these plots, each point represents the average indoor temperature for a day plotted against the daily outside temperature or the running mean temperature.

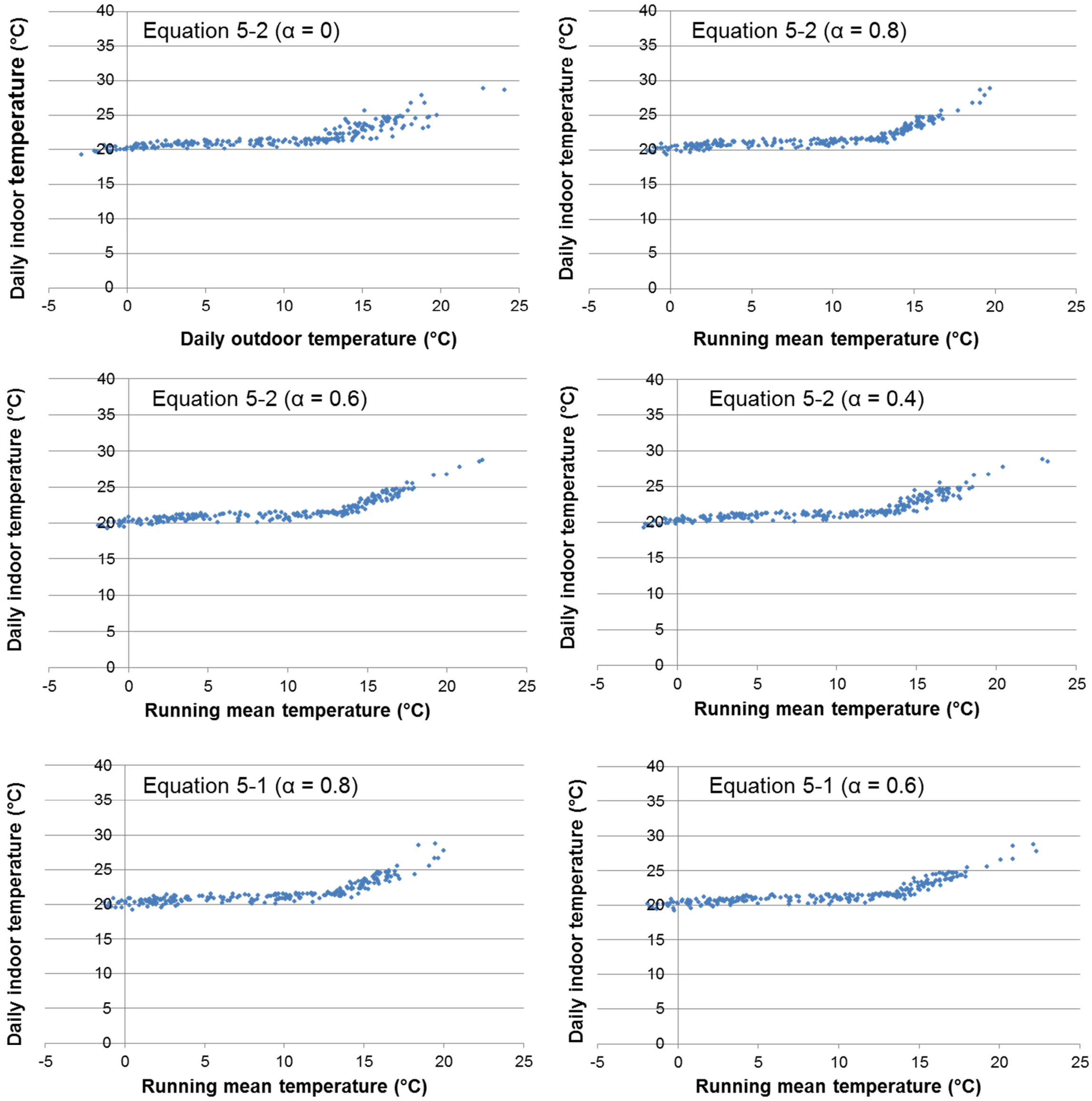


Figure 5-1. Daily indoor temperature against daily outdoor temperature using six different techniques for calculating a running mean based on temperatures measured in the living room of a single dwelling between July 2009 and February 2010.

The plots were inspected visually and it was concluded that a running mean temperature calculated by Equation 5-2 and an alpha value of 0.6 produced the plots with the least scatter. Therefore, this method was used for subsequent analysis.

It was observed that in most of the dwellings the plots could be broken into two sections which represented heated (winter) and unheated periods (summer). In most dwellings there was a noticeable change in gradient between the two portions of the plot (Figure 5-2). It is assumed that the running mean temperature where the regression lines of the heated and unheated points meet is the temperature below which occupants start to heat their homes and is called the heating threshold temperature. In many dwellings this temperature will be related to the thermostat setting. Heating systems may be on constantly but only deliver heat when indoor temperatures drop below the thermostat setting. As outdoor air temperatures drop during the autumn indoor temperature decreases below the thermostat setting and the boiler is switched on. In other dwellings heating systems will be turned off during the summer and the threshold temperature is an indicator of when occupants feel cold enough to turn the heating back on.

To ascertain the heating threshold temperature the 249 plots were visually inspected. This process is depicted in Figure 5-2, the two lines of best fit representing heated and unheated period are shown as well as the running mean temperature when they cross. As the lines of best fit were drawn by hand only whole numbers for the heating threshold temperature were recorded. This method was used, as a mathematical approach would have required choosing a cut off between heated and unheated periods. It was observed (as shown below) that there was often cross over, i.e. a number of days when the running mean temperature was similar but where sometimes heating was used and sometimes it was not, so an exact cut off point was not easy to identify. In this example the heating threshold temperature is approximately 14℃. Scatter plots of all dwellings are shown in appendix A.1.2.

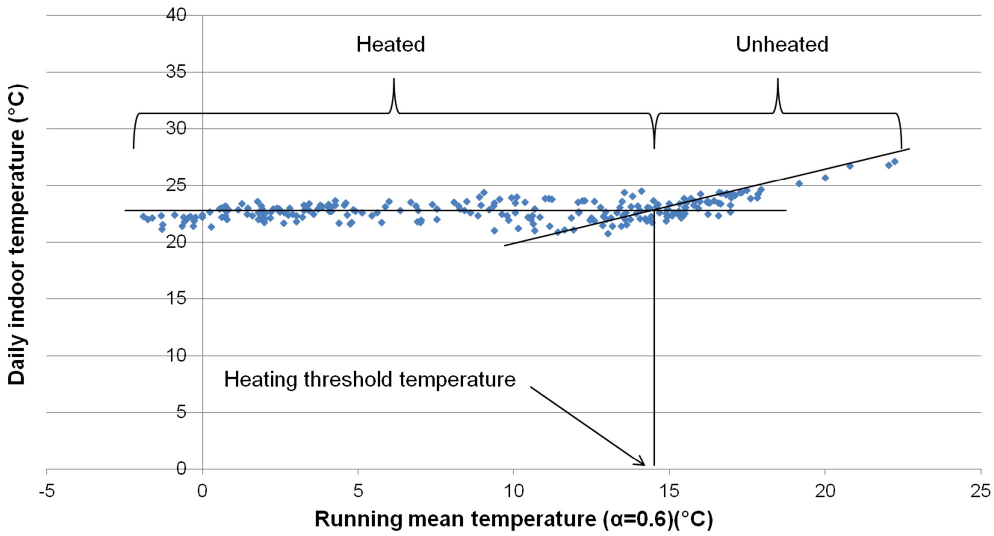


Figure 5-2. Scatter plot of indoor temperature against running mean temperature showing the method used to identify the temperature at which heating is used. Temperatures measured in the living room of a single dwelling between July 2009 and February 2010.

It was not possible to identify the threshold temperature using this method in all cases. For example, in the dwelling shown in Figure 5-3 the average indoor temperature continues to decline below a running mean temperature of 14℃, suggesting that heating is not used constantly at lower running mean temperatures. This may be related to this dwelling having very short heating periods and consequently low average daily temperatures; some scatter may also be related to periods when the dwelling was unoccupied.

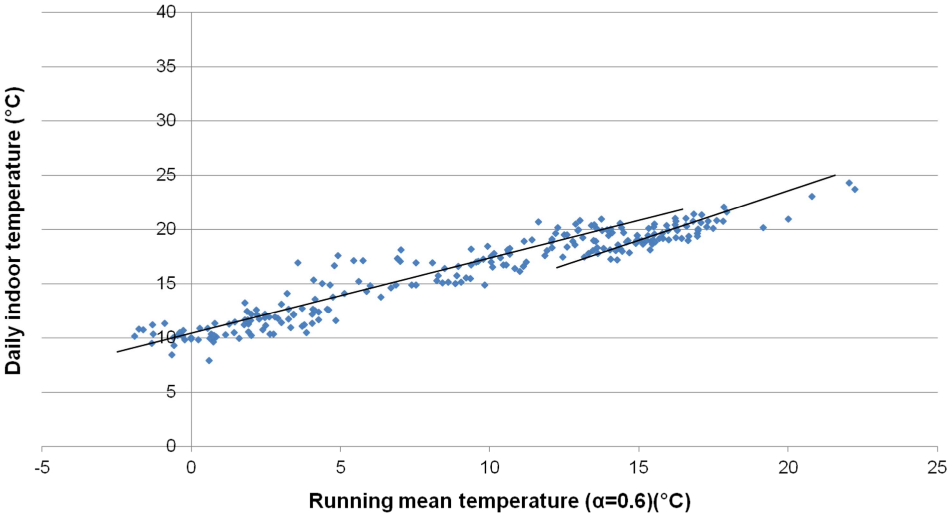


Figure 5-3. Scatter plot showing daily indoor temperature against running mean temperature, showing example of a dwelling where a heated and unheated period could not be identified. Temperatures measured in a single dwelling between July 2009 and February 2010.

Many of the dwellings showed periods where heating was not used on days with low running mean temperatures (Figure 5-4). In this example there are many days where little or no heating is evident. This is likely to be related to days when the dwelling was unoccupied. In the dwelling in Figure 5-4 it was not possible to ascertain the threshold temperature as heating was used sporadically at running mean temperatures below 10℃ and only used consistently when the running mean temperature dropped to 5℃. When clear lines of best fit could not be drawn because heated and unheated periods were not clear the heating threshold temperature could not be identified; this was the case for 30 dwellings (8% of the sample).

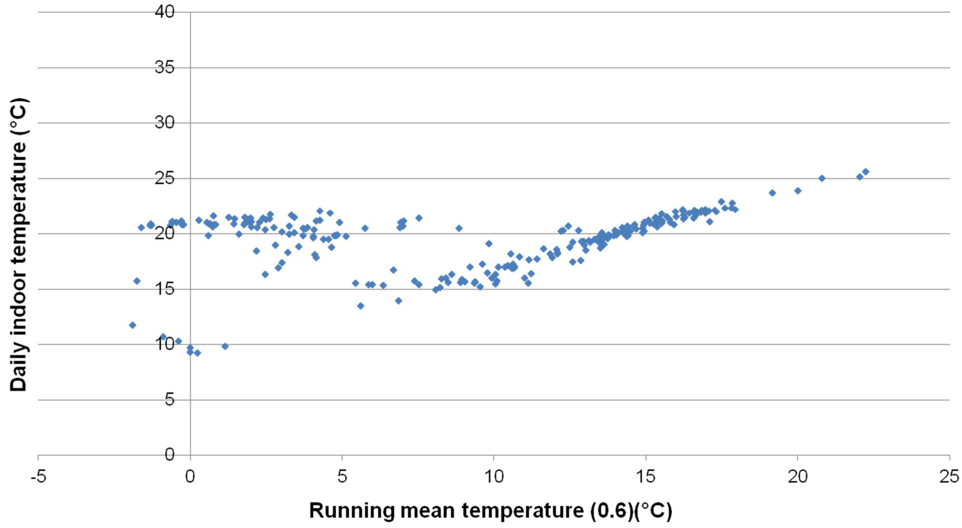


Figure 5-4. Scatter plot showing daily indoor temperature against running mean temperature, showing a dwelling where heating was used inconsistently. Temperatures measured in a single living room between July 2009 and February 2010.

5.1.2 Results of start of heating season

The heating threshold temperature describing the running mean temperature after which heating is used was estimated for 229 dwellings (

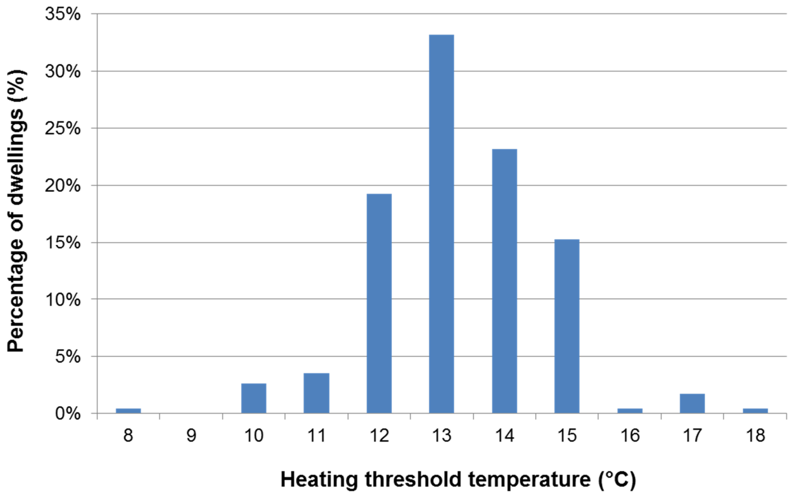


Figure 5-5). The average heating threshold temperature was 13.3℃ (Standard deviation 1.4℃). 76 of the dwellings heated their homes below a threshold temperature of 13℃. The highest and lowest thresho ld temperatures were 18℃ and 8℃ respectively. The range of threshold temper atures suggests that some dwellings are heated throughout the year and that others are only heated during the coldest winter months. In the monitoring period 2009-2010 the T_{rm} is over 18℃

for only a handful of days (only seven days in the summer of 2009). It fell steadily during the autumn but was not constantly below 8℃ until November (Figure 5-6).

The lack of resolution of threshold temperatures is a product of the method chosen here and it is likely that threshold temperatures do not increase in integer steps but are normally distributed as suggested by the shape of the histogram (

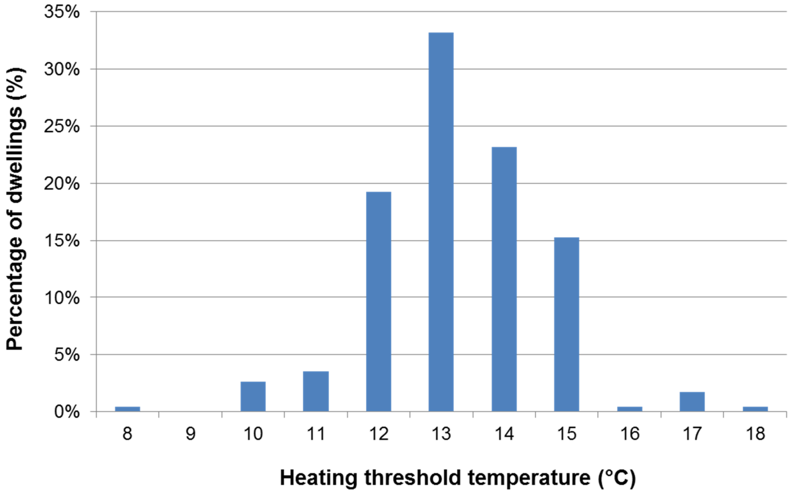


Figure 5-5).

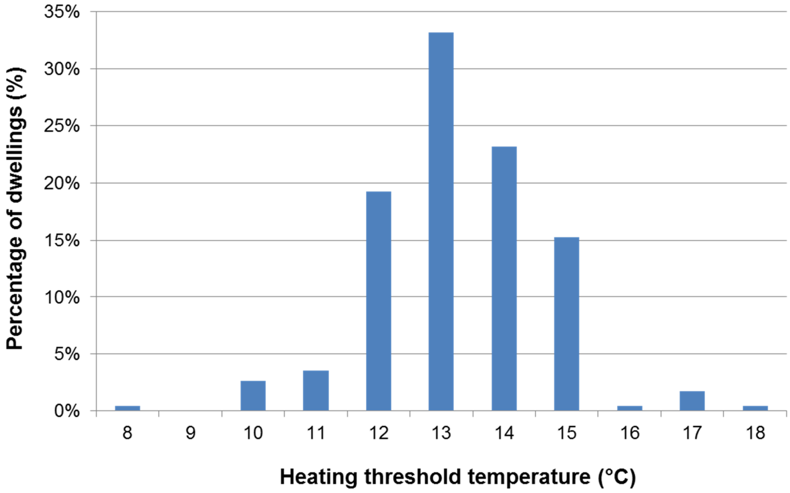


Figure 5-5. Histogram showing the frequency of threshold temperatures and percentage of dwellings heated under the threshold temperatures in 229 dwellings in Leicester.

The heating threshold temperature was used to identify the first heating day in each of the dwellings. As household occupants are able to adapt to changes in outdoor air temperatures by increasing levels of clothing, it was assumed that heating was used when the running mean temperature was lower than the threshold temperature for three consecutive days. This assumption also meant that the dates calculated for the start of the heating season were not bunched after a single cold day but spread out when temperatures were consistently lower than each heating threshold temperature.

It is noted that the calculation of heating degree days which are often based upon a daily temperature of 15.5℃. The average threshol d temperature calculated here is slightly lower than this figure but this may be related to the use of a running mean which accounts for occupant's ability to adapt to changes in outdoor conditions.

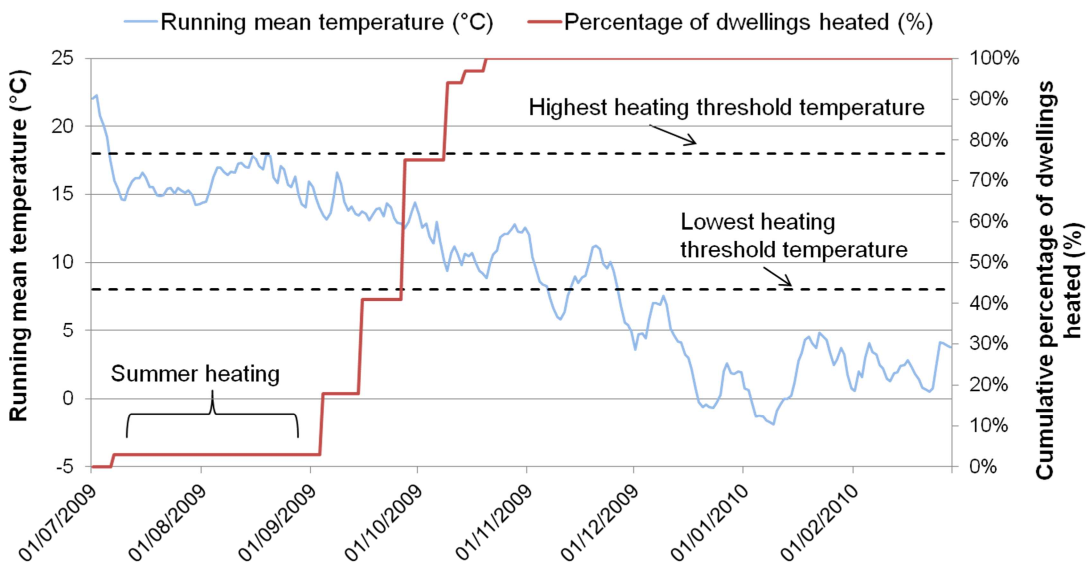


Figure 5-6. Date when heating period started during the 2009-10 heating season based on the threshold temperatures of 249 dwellings in Leicester.

Figure 5-6 shows the date at which the threshold temperature (or heating on condition) is reached in all 229 dwellings. Again, as stated above, the steps are an artifical consequence of the analysis method and in reality it is expected that heating will begin in homes according to a smooth curve that roughly follows the pattern shown here. The plot also suggests that a small number of dwellings will be heated throughout the summer (3% of dwellings had a threshold temperature of 16℃ or above). At the beginning of September the o utdoor temperature fell and after 4th September 15% of dwellings would be heated heated and a further 23% after 15th September. As the outdoor air temperature continues to fall two more significant thresholds are met on the 27th September and the 9th October which lead to the start of the heating season in 33% and 19% of dwellings respectively. Outdoor air temperatures dropped lower still at beginning of November which resulted in all dwellings being heated by 9th November until the end of the monitoring period on 28th February 2010.

Six dwellings (3%) had a threshold temperature of 16℃ or over which suggests they are heated during the summer period (Figure 5-7), 88 of the dwellings (38%) started being heated during the first half of September (Figure 5-7) and 135 dwellings (59%) started heating from mid-September onwards.

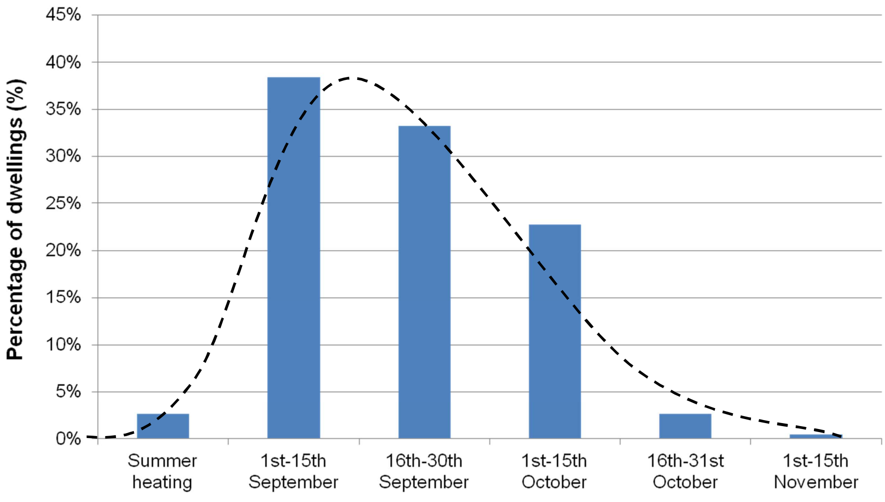


Figure 5-7. Histogram showing when the start of heating season in 229 dwellings in Leicester during 2009.

To calculate the rest of the heating metrics it was important to establish a period when all of the dwellings are heated. 100% of the dwellings were heated at temperatures below 8℃ this occurred on 9th November and it is therefore assumed that all dwellings are heated constantly after this date. Further analysis was therefore carried out on the three month period December 2009 to February 2010.

The author is unaware of any other study which has attempted to use empirical data to identify the start of the heating season and therefore no direct comparison was possible. To validate the findings of the start of the heating season daily gas use data was sourced from the National Grid (National Grid, 2012). Daily gas use for the East Midlands was plotted with daily outdoor temperature for the period between 1st July 2009 and 28th February 2010. During periods when the outdoor temperature is very low more gas is used as heat loss from dwellings is increased. It can be observed that gas use is relatively constant throughout the summer but as temperatures drop during September and October more dwellings are heated. Using this method it is not possible to determine how accurate the calculation of start of heating season is as drops in temperature are related to increased gas use whether more households start to heat their homes or not but it does suggest that in 2009 there was a gradual uptake of heating from mid-September onward temperatures drop. It should be noted, however, that these are total gas use figures and consequently include domestic, non-domestic and industrial use.

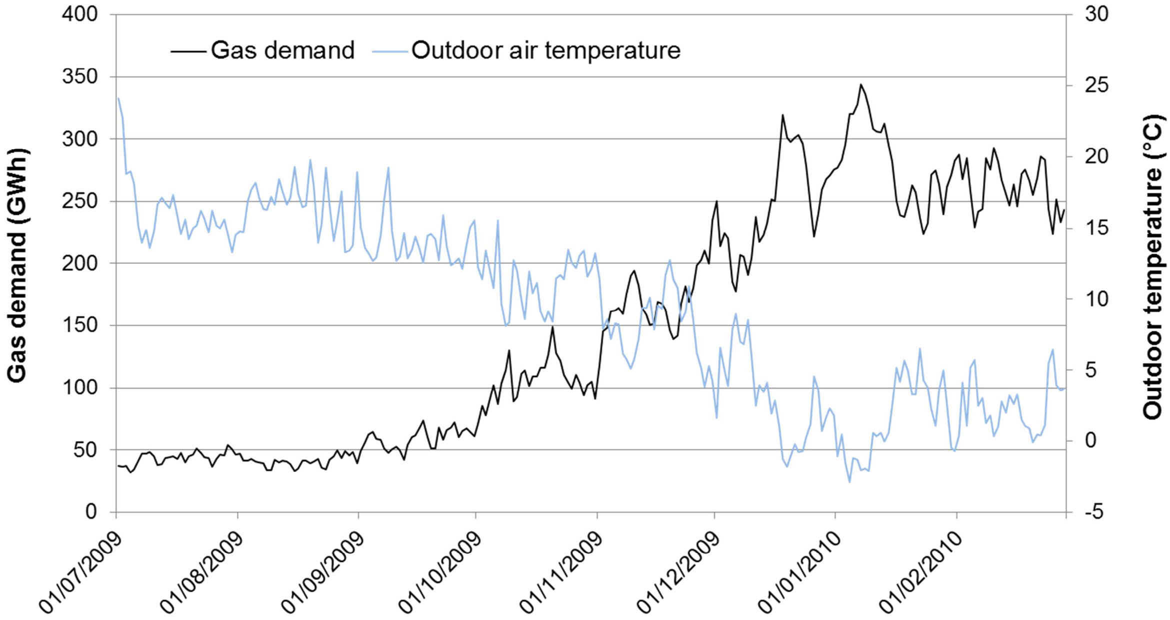


Figure 5-8. Daily gas demand for the East Midlands region and outdoor air temperature for the period July 2009 – February 2010.

Analysis of variance (ANOVA) was used to see if threshold temperature was related to the mean winter temperature measured in the living room and bedroom, a statistically significant relationship was established (p=0.001 & 0.021) for both rooms. This suggests that the threshold temperature is related to thermostat setting i.e. a high thermostat setting may result in a high threshold temperature. The heating will turn on earlier in the year in dwellings with a higher thermostat setting resulting in a longer heating season as well as higher mean winter temperature.

5.2 Heating practice metric 2 - heating pattern

5.2.1 Identification of heating pattern

The second heating practice metric is heating pattern, which is defined as the number of times per day that heating is predominantly used in each dwelling. It is important to understand the types of heating pattern used as it can give an insight into when dwellings are heated.

During the winter most dwellings are heated with central heating systems controlled with a timer. Examples of possible heating patterns are single, where heating is only used for one period each day, or double, where heating is used for twice each day.

To identify which heating pattern was used, two graphs were plotted for each dwelling. These were average day temperature profiles for living rooms during the period between December 2009 and February 2010, also plotted on these graphs was the percentage of hours heated at each hour (based on technique 2 discussed in section 5.3.3), and the living room and bedroom temperature traces for the whole of February 2010. Examples of these plots are shown in **Error! Reference source not found.** and Figure 5-10. Weekdays were chosen as it was assumed that heating would be more consistent on weekdays and therefore the most prevalent heating pattern would be easier to identify.

Error! Reference source not found. shows a typical example of an average temperature profile with one heating period. In this dwelling the heating is turned on at 8:00am and heating continues until 9:00pm when peak temperature is reached. The living room cools over night from a peak temperature of approximately 23℃.

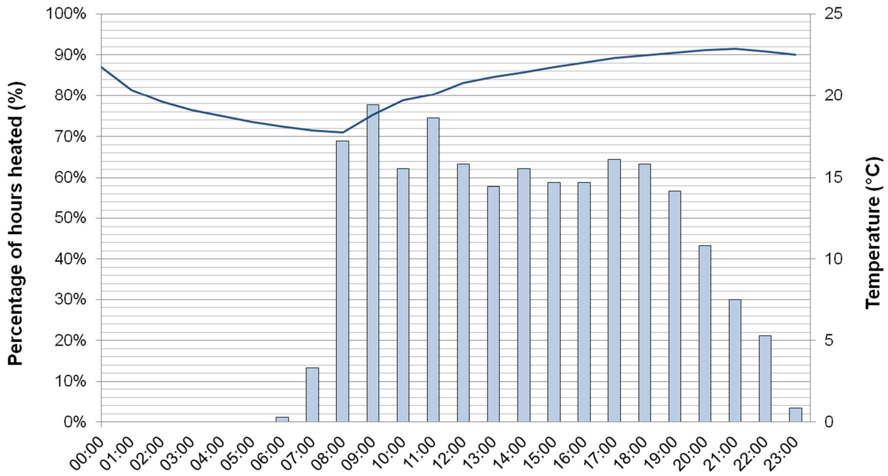


Figure 5-9. Average winter day in a single dwelling showing indoor temperature and percentage of hours heated with a typical single heating pattern. Temperature measured in one home in Leicester between December 2009 and February 2010.

Figure 5-10 shows an example of the monthly plot showing indoor and outdoor temperature from 1st February 2010 to 28th February 2010. In this dwelling the living room is heated to warmer temperatures than the bedroom. The predominant heating pattern is a double heating period. The heating is turned on for a short time in the morning and the second heating period has a longer duration. Peak temperature is reached at the end of the second heating period. These two examples do not provide any evidence of thermostatic control as temperatures increase until the heating is turned off.

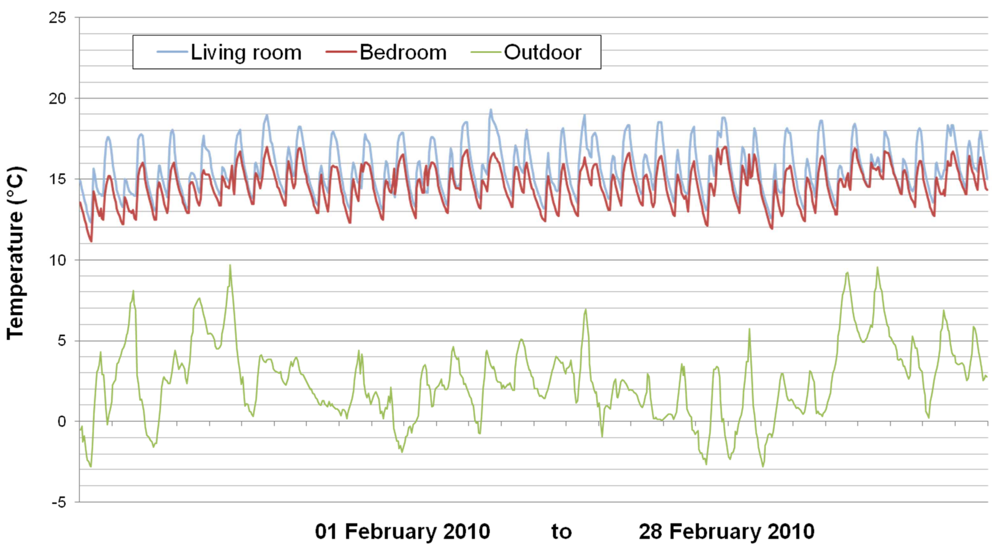


Figure 5-10. Monthly temperature plot from one dwelling for the period 1st February 2010 to 28th February 2010. The predominant heating pattern used during this period is a double heating period.

The average temperature plots and plots of indoor and outdoor temperature in both living room and bedroom were scrutinised visually to identify which heating pattern was most commonly used. When it was not possible to identify the predominant heating pattern from the two plots, graphs of a number of individual days were studied to try and identify when heating was used in each dwelling. Each household was categorised into one of four heating patterns single, double, multiple or those which could not be categorised.

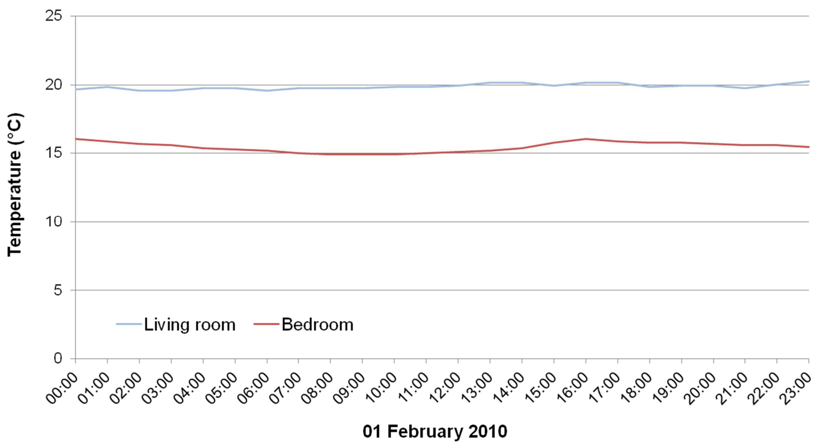


Figure 5-11. Constant heating pattern used in one household hourly temperature measured on 1st February 2010.

There was some evidence of dwellings that were heated constantly during some period during the winter. This can be observed in Figure 5-11 where the temperature of the average winter weekday is almost constant in the living room around 20℃, slight variations can be observed which may be related to boiler cycling. These dwellings however, were not often heated constantly throughout the whole heating period and therefore it was not possible to categorise them. As the aim was to identify the predominant heating patterns the differences between weekdays and weekends were not studied.

5.2.2 Heating pattern results

This section describes the heating patterns found in the 249 dwellings. Two heating patterns dominate the sample; single and double, where heating is used once and twice per day respectively (

Table 5-2). 28 (11%) of the dwellings had inconsistent heating patterns and could not be categorised. This is an important finding as domestic energy models tend to assume that heating is used consistently throughout the heating season.

Table 5-2. Predominant heating pattern used in 249 dwellings in Leicester

Type of heating pattern	Number of dwellings	% of dwellings
Single	82	33%
Double	127	51%
Multiple	12	5%
Unable to categorise	28	11%

Double heating patterns where occupants used their heating twice each day were the most common with 51% of the sample. Double heating patterns are likely to be used by households with occupants in full time employment; this is explored further in section 5.7. In these dwellings occupants heat their homes briefly in the morning before they go to work and then again in the evening when they return home.

Single heating patterns were the second most common making up 33% of the sample. It is expected that dwellings with a single heating pattern will predominantly be households with occupants who are retired, unemployed or looking after young children. These dwellings may have longer daily heating periods than those with double heating patterns and where little or no thermostatic control is observed the longer heating periods are likely to result in higher demand temperatures.

Multiple heating patterns were observed in 5% of the dwellings. In these households heating is used more than twice a day consistently enough to be categorised. It is expected that dwellings with multiple heating patterns are those with high heat loss and occupants that are present in the house during the day. Multiple heating patterns may also be used in dwellings where different household occupants are working shifts and therefore occupying the dwelling at different times of the day.

5.3 Techniques used for further analysis

The remainder of the heating practices discussed in this thesis are based upon the period December 2009 to February 2010. To calculate the following metrics for the heating practices a number of analysis techniques were developed and applied to the data. This section introduces the various analysis techniques that were tested.

Most of the heating practice metrics build upon the identification of when heat is delivered to the rooms and consequently the most important part of this work is to understand, where possible, when the heating systems were turned on and off.

It should be noted again that the aim of this work is to develop heating practice metrics which give insight into average heating use and identify whether the heating practices are related to technical or social descriptors. It is recognised that households change the way they use their heating throughout the winter but, although this is touched upon, it is not the focus of this work.

5.3.1 Development of technique 1

The starting point of the calculation to identify when heating was used was the assumption that when it is cold outside heat is delivered when the indoor temperature increases. This was considered reasonable as during winter periods the difference between indoor and outdoor temperatures is high and solar heat gains are low. It is recognised, however, that there may be times of high internal or solar heat gains and this is therefore considered when developing this method.

Only living room temperature was used for this calculation as it was assumed that in most dwellings the living room temperature would be controlled more carefully and would therefore result in a more accurate estimation of when heat was being delivered.

Initially heat was assumed to be delivered at the time T_t if the following condition was met:

$$T_t - T_{t-1} > 0 \quad \text{[Equation 5-3]}$$

Where T_t is the temperature at the first hour and T_{t-1} is the temperature at the hour before T_t.

Previous studies which have estimated the daily heating period based on indoor temperature measurements have used this simple method (Shipworth et al., 2010), however, it is unable to consider periods of thermostatic control, when the indoor temperature will not rise but is maintained and therefore a second clause was added. The second clause assumed that if heat had been delivered during either of the previous two hours and the temperature fell less than 0.1℃ then the heating was still on. The figure of 0.1℃ was reached using a combination of trial and error and observation of temperature traces and considers that the temperature in a single space can fall slightly when the heating is turned on before the thermostat setting is again reached (see Appendix 3).

The second clause can be expressed as:

$$(T_{t-1} - T_{t-2} > 0 \; or \; T_{t-2} - T_{t-3} > 0 \; and \; T_{t-1} - T_t > -0.1)$$ [Equation 5-4]

The final calculation method combines equations 5-3 & 5-4 and assumes that heating was in use at T_t if the following condition was met:

$$Heating\ is\ in\ use\ at\ T_t \quad if\,(T_t - T_{t-1} > 0)\ or\ \ if\,(T_{t-1} - T_{t-2} > 0\ or\ T_{t-2} - T_{t-3} > 0\ and\ \ T_{t-1} - T_t > -0.1)$$

[Equation 5-5]

The difference between equation 5-3 and 5-5 is illustrated in Table 5-3.

Using this method it was possible to identify when heating was on or off at each hour of the day in each dwelling.

Table 5-3. Explanation the two calculation methods for identifying when heating was in use

		Heat delivered at hour (yes, no)	
	℃	Equation 5-3	Equation 5-5
T_t	17.2		
T_{t+1}	16.9	0	0
T_{t+2}	18.1	1	1
T_{t+3}	18.7	1	1
T_{t+4}	18.7	0	1
T_{t+5}	16.5	0	0

To validate the calculation method temperature graphs of each living room for a single day (1st February 2010) were plotted (Figure 5-12). The dwelling shown in the plots has a single heating period between 6:00am and 9:00pm. Temperature increases quickly between 6:00am and 8:00am after which it slows down. After 8:00am when the temperature remains constant (or falls less than the 0.1℃) the

Equation 5-3 method records that the heating is not on. During this time the assumption is that the heating is cycling and the boiler does not constantly deliver heat to the living room, where the sensor is situated. In the example related to Equation 5-5 which takes into account periods when temperature is not increasing but being maintained near the thermostat setting one constant heating period between 6:00am and 9:00pm is recorded. It is concluded that for the purpose of this study, which aims to understand when occupants have programmed their heating systems to turn on and off, and not solely when heat is delivered to the space that the method described by Equation 5-5 is the most appropriate.

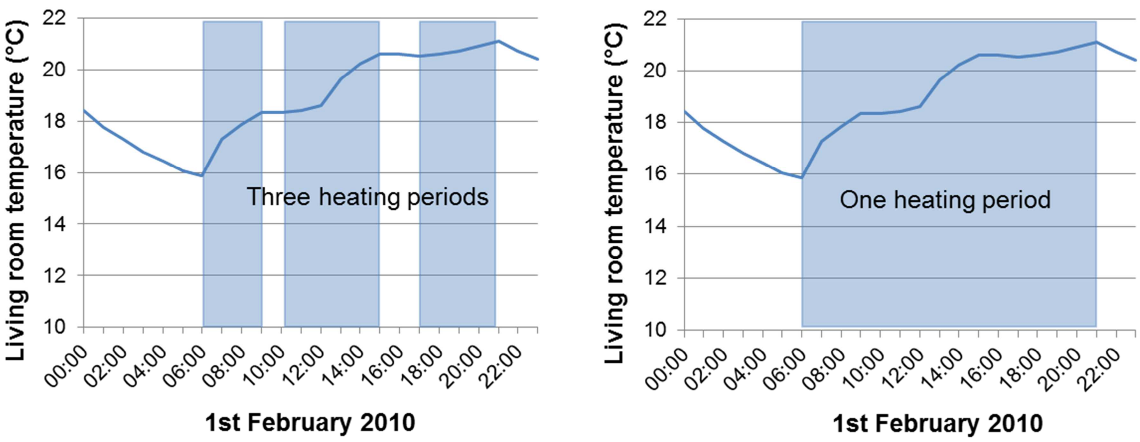


Figure 5-12. Comparison of daily heating period calculation methods based on equation 5-3 (left) and 5-4 (right) for a single day in one home.

Plots showing the living room temperature measured on 1st February 2010 and the heating period calculated were plotted for all 249 dwelling and are shown in appendix A.1.6.

5.3.2 Limitations of technique 1

Equation 5-5 was applied to all the data for the period December 2009 to February 2010 to estimate the daily heating period. Daily heating period was calculated by taking the sum of the number of heating hours for each day and then averaging this for the whole analysis period (December – February).

This method for the calculation of daily heating period has number of limitations:

- It is expected that there will be some dwellings where periods of high solar or internal heat gains are counted as heated periods. This will result in a longer daily heating period. It is noted that this method does not account for time of day i.e. a small temperature increase of say 0.1℃ between 12:00pm and 1:00pm would be counted as an hour of heating but is just as likely to be result of a solar heat gain.
- As daily heating period is an average of all days it is difficult for dwellings to be found to have very long heating periods as a result of periods where dwellings are unoccupied. For example, there may be dwellings which are heated constantly during winter periods (daily heating period = 24 hours) but as a result of times when the dwelling is unoccupied the average is reduced.
- In homes that are very well insulated longer daily heating periods could result as temperatures may not fall when heating is turned off. This is especially likely on mild days.
- As shown in the placement experiment discussed in Appendix 3, boiler cycling results in indoor temperatures increasing and decreasing during the heating period, it is not possible to know at which point in this cycle the hourly temperature readings are taken. In some dwellings a threshold of 0.1℃ (as used in Equation 5-5) may be too small. This suggests that calculation based on hourly temperature data is likely to lead to inaccurate results.

For these reasons it was concluded that a new way of calculating daily heating period was required. As this work is interested in identifying the variation of average heating practices across the housing stock and not how the heating period might change over the course of the heating season a profile approach based on the percentage of days that heating was observed at each hour during the analysis period was developed.

5.3.3 Technique 2

Technique 2 builds on technique 1 and explores a novel way of identifying the predominant times that heating systems are turned on and off.

Using Equation 5-5 the percentage of days during the 90 day analysis period when heat was deemed to be delivered at each hour was identified. If heat was delivered at 7:00am every day during the analysis period then the percentage of hours heated at 7:00am was recorded as 100%. If heat was delivered at 7:00am on half of the days then 50% was recorded.

An example of this method is shown in Figure 5-13. The calculation method suggests that the heating comes on at either 8:00am or 9:00am. The end of the heating period is usually 11:00pm but on 13% of days, however, the heating is on at 12:00am. Heating is most commonly used at 10:00am (97% of the days).

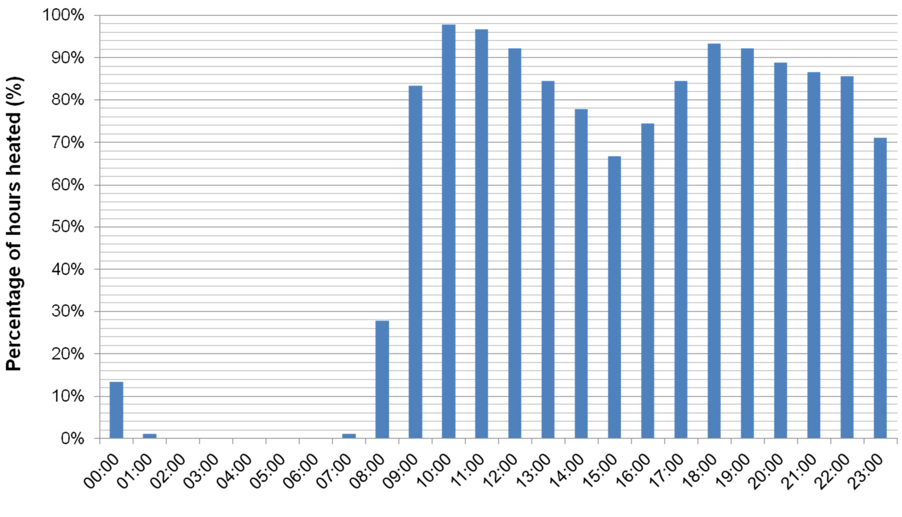


Figure 5-13. Percentage of days when heating was deemed to be on at each hour of the day for the period December 2009 to February 2010 in a single living room.

In order to understand when heating was turned on the hour before heating was observed was important, as an increase in indoor temperature seen at 8:00am is assumed to relate to the heating being used between 7:00am and 8:00am. To take this into account the hours were shifted back so that if 7:00am was calculated to have 90% of hours heated this was aligned with the 6:00am timestamp and therefore the time when heating system came on could be considered.

By visually inspecting the percentage of hours heated plots it is possible to identify a number of trends including; the time heating is switched on and off, the predominant heating pattern and how consistently dwellings are heated – i.e. how often household occupants change their heating settings. Percentage of hours heated plots for each dwelling are included in Appendix (A.1.7).

The average percentage of hours heated plot gives an indication of the average heating pattern and consistency of heating across all 249 homes (Figure 5-14). Two peaks one in the morning and one in the evening can be observed but the percentage of hours heated does not fall below 50% during the time between 8:00am and 9:00pm.

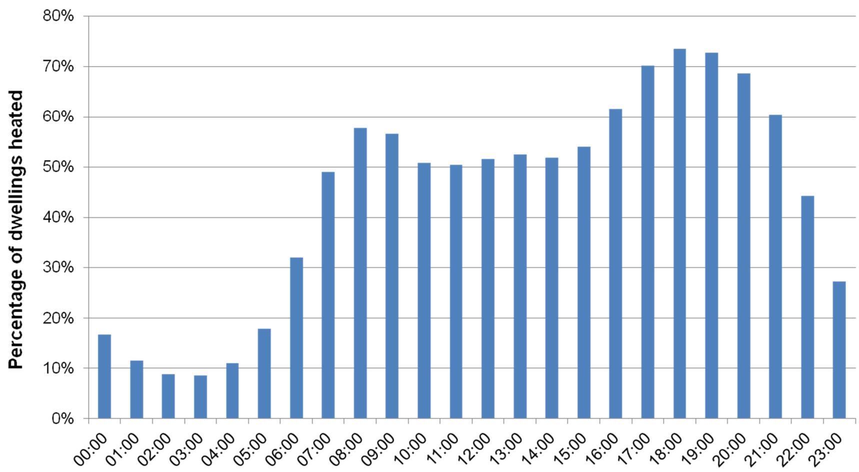


Figure 5-14. Average percentage of hours heated for the period December 2009 to February 2010 in all 249 dwellings.

Percentage of hours heated were plotted for each dwellings according to weekday and weekend periods to identify whether dwellings were heated significantly differently on these days. No significant trends were observed so it was decided to take the analysis period as a whole to maximise the number of analysis days and therefore reduce the impact of the small number of days when unusual heating behaviour is observed.

5.3.4 Identifying the start and end times of heating

A number of methods for identifying the on and off times of heating based on the percentage of hours heated were trialled. The first method calculated the start time of heating as the first instance in the day when heat was deemed to be delivered on more than 50% of the days. In the same way the end time of heating was the last instance in the day when heat was deemed to be delivered more than on more than 50% of the days. This method, however, underestimated the heating period in dwellings with inconsistent heating patterns (i.e. start and end times of heating are changed regularly). A second method was consequently required.

The start time of heating was selected as the first hour when heating was used 10% or more often than the previous hour (a higher cut off of 20% was initially trialled but this again led to many dwellings having very short heating periods). For example, if heating is never used at 5:00am, used 6% of days at 6:00am and used 28% of days at 7:00am the start time of the daily heating period would be 7:00am.

It is recognised that the cut off value of 10% will result in longer heating periods than a higher cut off in some dwellings, but as using a higher cut off reduced the potential sample size for further analysis significantly the lower cut off was chosen. As the aim of this work is to compare the variation in heating practices across the housing stock this method was deemed appropriate as this method preserved the amount of variation between dwellings.

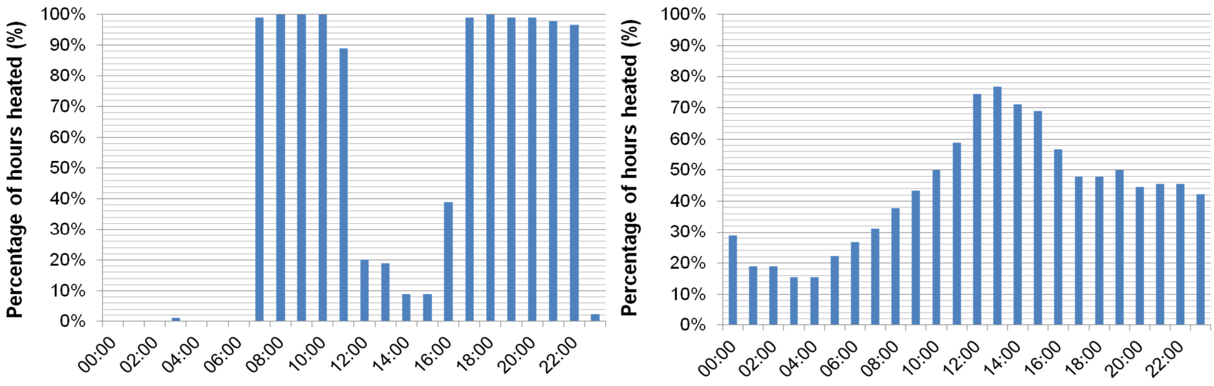


Figure 5-15. Example of percentage of hours plots in single dwellings with consistent (left) and inconsistent (right) heating patterns.

In dwellings with inconsistent heating patterns, i.e. the timer settings are changed regularly or heating is turned on and off manually when required, it is more difficult to identify the start time of the heating period and the method is therefore less accurate in these dwellings. This is highlighted when comparing dwellings which have consistent and inconsistent heating patterns (Figure 5-15). The dwelling on the left has a very consistent double heating pattern. Heating is turned on at 7:00am on 97% of the days during the analysis period and the first heating period usually lasts 5 hours. The second heating period starts predominately at 5:00pm and lasts 6 hours. The dwelling on the right of the figure is heated most commonly in the day with the peak percentage of hours heated of 77% occurring at 2:00pm. In this example it is not possible to identify a start time of heating period as heating is used inconsistently.

5.3.5 Limitations of technique 2

There are a number of limitations that result from the assumptions and calculation method used to establish the start and end times of heating. As stated previously it was not possible to accurately identify the start or end times in dwellings with inconsistent heating patterns using this method. Also start and end times derived in dwellings with inconsistent heating periods and those with multiple heating periods were also not reliable enough to report.

As this analysis is based on hourly temperature data it is not possible to identify heating periods at a higher resolution, this is a weakness as heating is not controlled solely at hourly intervals. For example, if a 15 minute period of heating occurred the temperature recorded by the sensors would be higher that at the previous hour and the calculation method would count one hour of heating leading to longer daily heating periods. Even in dwellings with very consistent heating (i.e. where heating is turned on and off at the same times every day) this could lead to an overestimation of daily heating period of up to two hours.

A third limitation is that the reported start and finish times are based on the first and last time heating is used on 10% of days during the analysis period. Therefore in dwellings which change their heating periods early start times and late end time of heating will be calculated. For example, if a household's most common start time of heating is 7:00am but on 12% of the days they turned heating on at 5:00am the method used here will identify 5:00am as the start time of heating. This method will consequently return what is the longest regular heating period and heating periods are likely to be two hours longer using this method in dwellings which do not have regular heating times.

The second and third weaknesses discussed here are partially related to the resolution of temperature data that was collected. It is expected that the method developed here to estimate the start and end times of heating periods would be greatly improved if temperature data was collected at 5 minutely intervals. It is consequently recommended that this method is applied to such a dataset in due course.

5.4 Heating practice metric 3 – start and end times of heating

The third heating practice metric is start and end time of heating and relates to the first and last time on a daily basis that heating is used regularly over the analysis period (December 2009 – February 2010). As the use of ground and air source heat pumps is likely to increase a better understanding of when heating occurs will be required so that future electricity demand can be planned for. Start and end times of heating can also be applied in dynamic simulation.

5.4.1 Calculation method used for start and end times heating

As discussed in section 5.3.4 the method used to identify the start and end times of heating periods was based on technique 2 which uses the percentage of hours when the heating was in use at each hour of the day. For example, in a dwelling where heating was controlled with a timer and heating turned on every day at 6:00am for the whole analysis period all of the hours at 7:00am would be recorded as heated and the percentage of hours heated would be 100%.

Start and end times are, therefore, only reported for dwellings with single and double heating periods as identified in section 5.2.

5.4.2 Results of start and end time of heating - single heating patterns

This section describes the variation in start and end time of heating in the 82 dwellings which had single heating patterns. Start and end times of heating are only reported for dwellings where both could be identified. The start of end time of heating could not be identified in 2 dwellings and therefore results here are based on 80 households.

16 (20%) dwellings had a start time of heating of 6:00am (Figure 5-16). 64% of dwellings started heating between 6:00am and 8:00am. The earliest start of heating time identified was 1:00am while the latest start time of heating was 6:00pm.

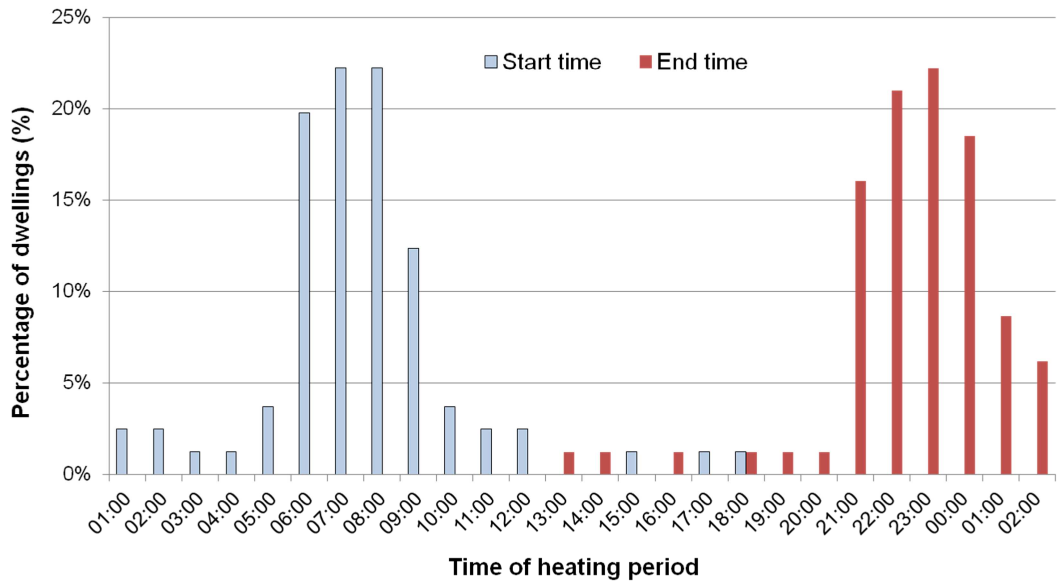


Figure 5-16. Histogram showing the start time of heating period in the 80 dwellings with a single heating pattern.

10:00pm and 11:00pm were the most common end times of heating with 17 (21%) and 18 (23%) dwellings respectively. The earliest end time of heating was 1:00pm but only 6 dwellings were found to have an end time of heating before 10:00pm. The latest end of heating time was 2:00am.

A number of end times of heating occurred later than expected (22 dwellings after 11:00pm). This may be related to the calculation method or how occupants heat their homes; it is expected that morning heating is controlled mainly via timers but heating in the evening is often overridden when required using the central heating timer or secondary heating. This pattern can be observed in many of the individual plots in appendix A.1.7. The first instance of heating in the morning is often more pronounced than the final heating in the evening which is more variable (i.e. there is a clearer start time than end time).

5.4.3 Results of start and end time of heating - double heating patterns

This section describes the start and end of the two heating periods in the 127 dwellings which were identified to have double heating patterns. Start and end times of heating for dwellings with double heating patterns when the start and end times could be identified for both heating periods. Either the start or end time could not be identified in 16 dwellings and therefore results here are based on 111 households.

76 (68%) dwellings had a start time of heating for the first heating period of 6:00am or 7:00am. The start times of the first heating period are comparable to those found in the dwellings with a single heating period. The earliest start time of heating was 1:00am and the latest was 9:00am. The median end time of first heating period was 9:00am this suggests that the first heating period is generally short. The earliest end time of the first heating period was 5:00am while the latest was 3:00pm.

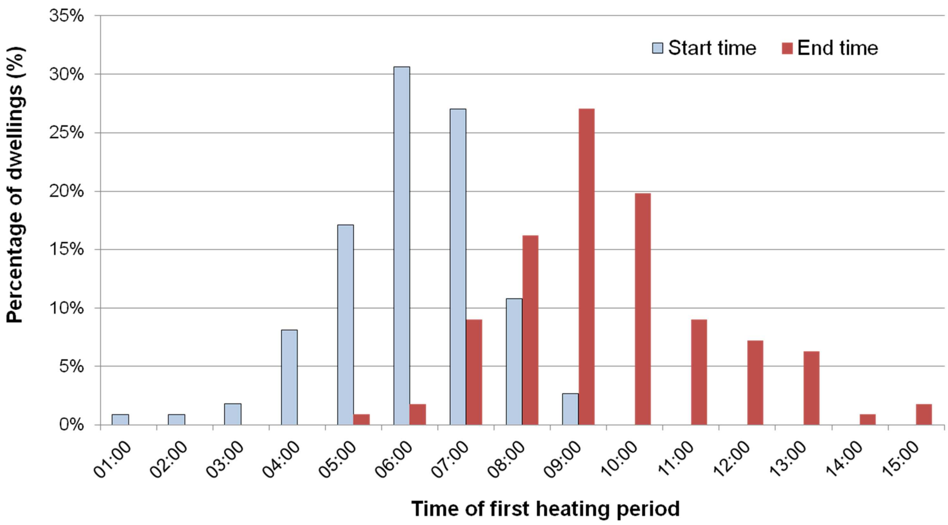


Figure 5-17. Start and end time of heating period in 111 dwellings with a double heating pattern.

The calculation method used was the least reliable for the start time of the second heating period. This is a result of the large variation in start times of the two heating periods. The most common start time of the second heating period is 4:00pm.

9:00pm was the most common end time of the second heating period two hours earlier than the end time of heating in dwellings with single heating periods. The earliest end of second heating pattern was 6:00pm while the latest was 2:00am.

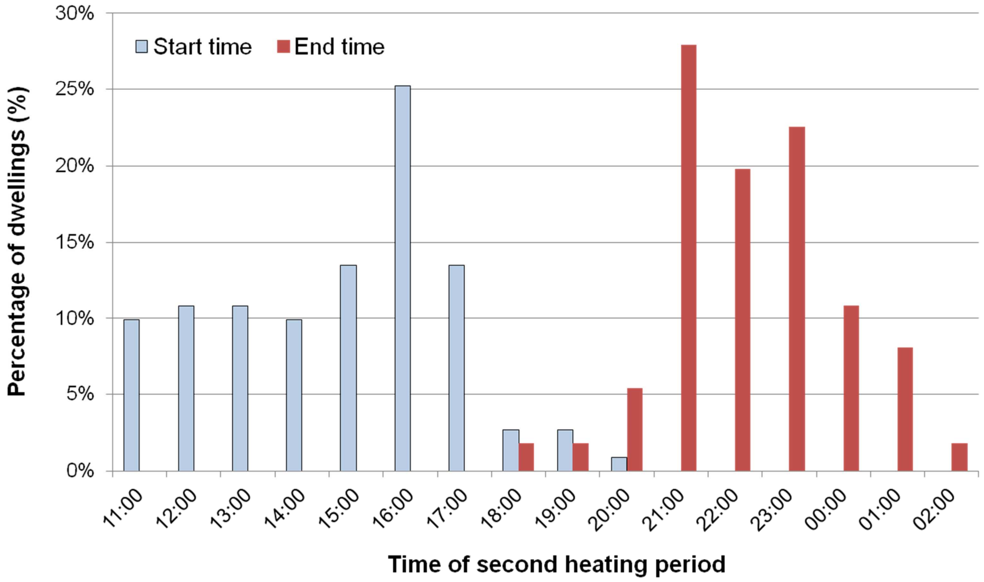


Figure 5-18. Start and end time of second heating period in 111 dwellings with double heating patterns.

The author is unaware of any other study which has reported the start and end times of heating and therefore no comparison is possible. These results, however, are compared to the heating practices used in energy models in section 7.2.1.

5.5 Heating practice metric 4 - Daily heating period

5.5.1 Calculation of daily heating period

The fourth heating practice metric calculated is daily heating period which is defined as the average number of hours that heating is used in a dwelling per day for the period December 2009 to February 2010. The aim of daily heating period is to establish when household occupants are actively controlling their heating. During these periods when heating is set on a timer and controlled using a thermostat the boiler will not be constantly working and therefore the indoor temperature will not always be increasing.

The approach used for calculating daily heating was based on Technique 2. The start and end times of heating for each dwelling period that was developed was based on the percentage of hours heated across the whole of the analysis period. Initially the most common start and end times of heating were identified. Then the daily heating period was calculated by taking the length of time of the heating periods. For example, in a dwelling with a single heating period it the start of the heating period was 8:00am and the end of the heating period was 21:00pm the daily heating period was 13 hours.

This method resulted in daily heating periods which were less affected by periods when dwellings were unoccupied and periods of high heat gain than the method used in previous research. However, in dwellings with inconsistent heating patterns, i.e. heating is turned on and off and different times each day longer heating periods resulted. This method is also likely to overestimate the daily heating period.

5.5.2 Daily heating period results

This section describes the variation in estimated heating periods across 191 dwellings where it was possible to identify start and end times of heating (80 with single heating patterns and 111 with double heating patterns). It was not possible to identify daily heating period in all 249 dwellings due to some dwellings having multiple heating periods where start and end times of heating could not be identified and others where the start and end times of heating were very inconsistent.

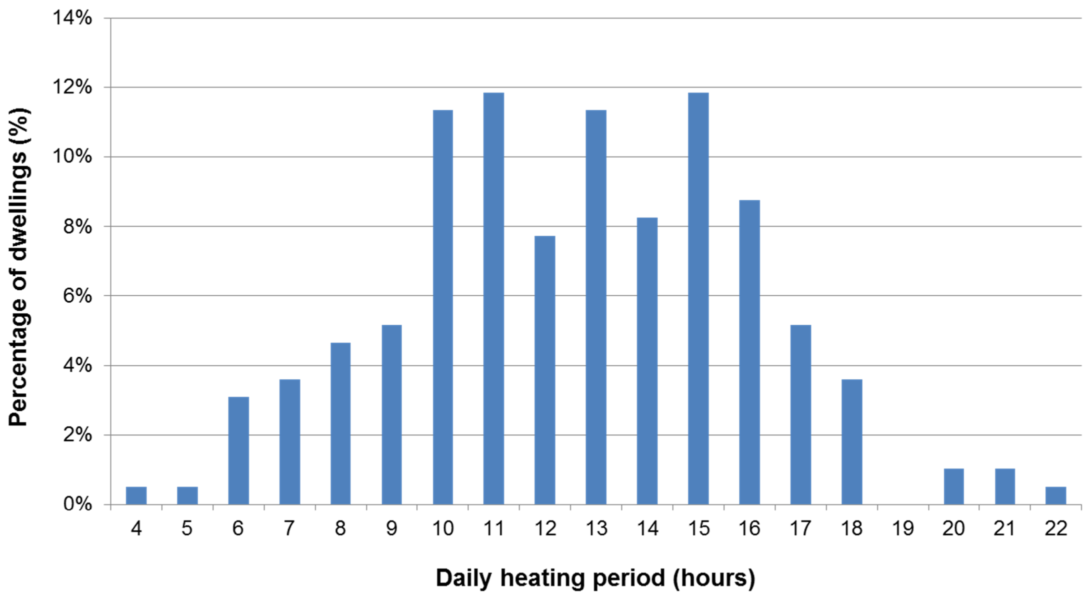


Figure 5-19 Histogram showing average daily heating period as calculated for 191 dwellings in Leicester.

The average daily heating period was 12.6 hours (standard deviation 3.4 hours) (Figure 5-19). The longest average daily heating period was 22 hours and the shortest was 4 hours. The average daily heating period is longer than the default heating period used in the BREDEM model which is 9 hours per day (section 2.3.3). It is noted that the BREDEM heating assumption may be related to occupant demand timing i.e. the times in the day when occupants require a comfortable temperature. This differs from the heating period which has been calculated here. Heating will be required for some time before the dwelling has reached the 'comfort' temperature. This is one possible reason why the heating periods calculated here are longer than those used in model predictions, however, the BREDEM literature and method is not clear about the specific dynamics relating to the idealised heating profile (Kavgic, 2010).

Previous temperature monitoring studies which have estimated daily heating period found shorter heating periods; Shipworth et al. (2010) reported estimated daily heating periods for weekdays and weekends of 8.3 and 8.4 hours respectively. Martin et al. (2006) used a more sophisticated monitoring approach to measure daily heating period with temperature sensors located directly on radiators and suggested that the average daily heating period was 8.8 hours. These studies, however, used a method which relied on temperature increasing in the monitored space and therefore did not take into account periods of thermostatic control or the effect of boiler cycling.

It is recognised that the method used here overestimates daily heating period; however, the method developed is able to identify dwellings which have long and short daily heating periods which previous studies have overlooked.

5.6 Heating practice metric 5 - Number of under-heated days

5.6.1 Calculating number of under-heated days

The fifth heating practice metric is the ‘number of under-heated days’ which describes the number of days during the heating season which are heated with shorter heating periods than are generally used.

In most dwellings occupants still heat their homes when the house is unoccupied to ensure that water pipes in the dwelling do not burst; only 24 dwellings (10%) had one or more days with no heating. Additionally, solar or internal heat gains my result in indoor temperatures rising during the day. Consequently, it is difficult and potentially misleading to calculate the number of days where no heating (or no temperature increases) is observed. The heating practice metric derived here is therefore number of under-heated days and aims to give insight into the number of days during the analysis period that a dwelling is either unheated or heated considerably less than usual.

Figure 5-20 shows the monthly temperature plot of one dwelling for February 2010, a number of days when the dwelling is unheated can be observed. During these days the indoor temperature drops until heating is used again. The average winter temperature and energy use will be lower in dwellings which have a high percentage of unheated days during the heating season.

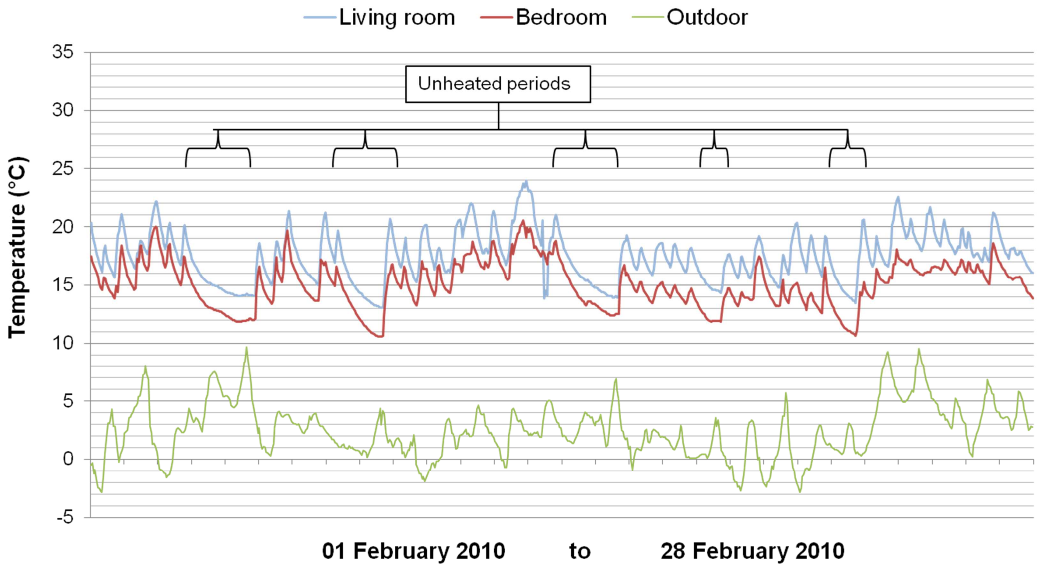


Figure 5-20. Monthly temperature plot of one household for the period of 1st February 2010 to 28th February 2010. Showing inconsistent heating patterns and periods where the dwelling is unoccupied.

Equation 5-3 (technique 1) was used to calculate the heating period used for each day of the analysis period. A dwelling is categorised as under-heated on a particular day if the heating period for that day is less than or equal to half of the average number of hours heated for the dwelling. For example, if the average number of hours heated in a dwelling is eight hours and one of the days four hours of heating was observed this would be counted as an under-heated day (Figure 5-21). This is shown in the plot below where 5 days are counted as under-heated as no heating was observed and a further 8 days were counted as under-heated as the daily heating period was half or less of the average number of hours heated for this dwelling. This dwelling is heated very inconsistently which suggests that the heating is controlled manually or the timer is often overridden. The most common daily number of hours heated is 10 which occurs on 15 days and 41% of days are heated for between 9 and 11 hours.

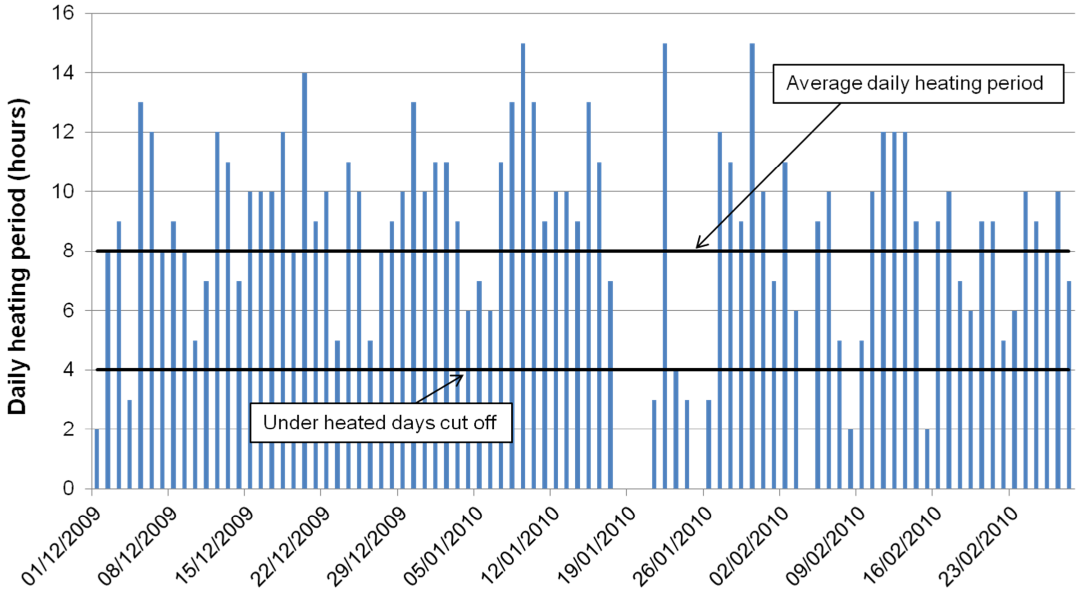


Figure 5-21. Example of a dwelling with 13 under-heated days during the 90 day period between December 2009 and February 2010.

Dwellings with a high proportion of under-heated days are likely to use less energy as a result of having shorter daily heating periods. The number of under-heated days will also impact on the calculation of the heating practice metrics which are calculated by averaging a daily estimation across the whole analysis period. For example, average temperature during heated periods is expected to be low in dwellings with a high proportion of under heated days.

5.6.2 Results of number of under-heated days

This section describes the variation in number of under-heated days across the 249 dwellings. The average number of under-heated days was 2.9 (standard deviation 4.4), (i.e. 3% of the 90 day analysis period). 96 (39%) of the dwellings had no under-heated days and 43 (17%) dwellings only had one under-heated day (Figure 5-22). 22% of the dwellings were under-heated for between two and four days during the analysis period. 8% of dwellings have ten or more under-heated days during the analysis period. As expected these dwellings have mean winter temperatures which are lower than dwellings with fewer under-heated days (p<0.01). The highest number under-heated days recorded was 38 (42% of the analysis period).

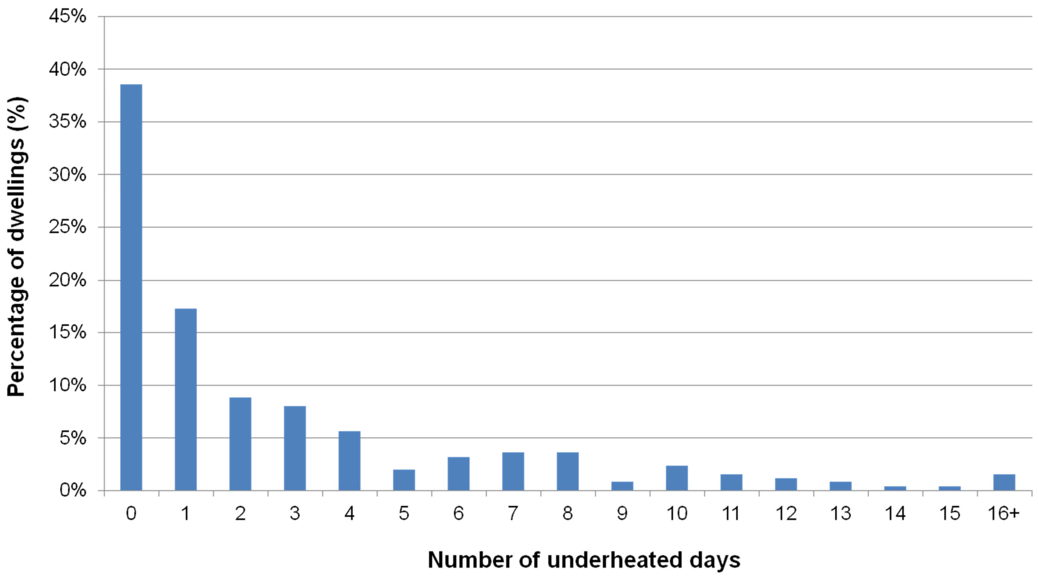


Figure 5-22. Number of under-heated days periods based on the period between December 2009 and February 2010 and temperature data collected in 249 dwellings in Leicester.

To identify if there were any patterns as to when dwellings were under-heated each day was categorised as heated of under-heated for each dwelling. The average number or under-heated dwellings on each day was then counted (Figure 5-23). The average number of under-heated dwellings on a particular day was eight (standard deviation 4.4). The most under-heated dwellings on a particular day was 20 (8% of dwellings) which occurred on the 26th February. No discernable pattern can be observed although the Christmas holiday (24th – 29th December) is one of two periods where a higher number of under-heated dwellings than average can be seen for more than three days in a row.

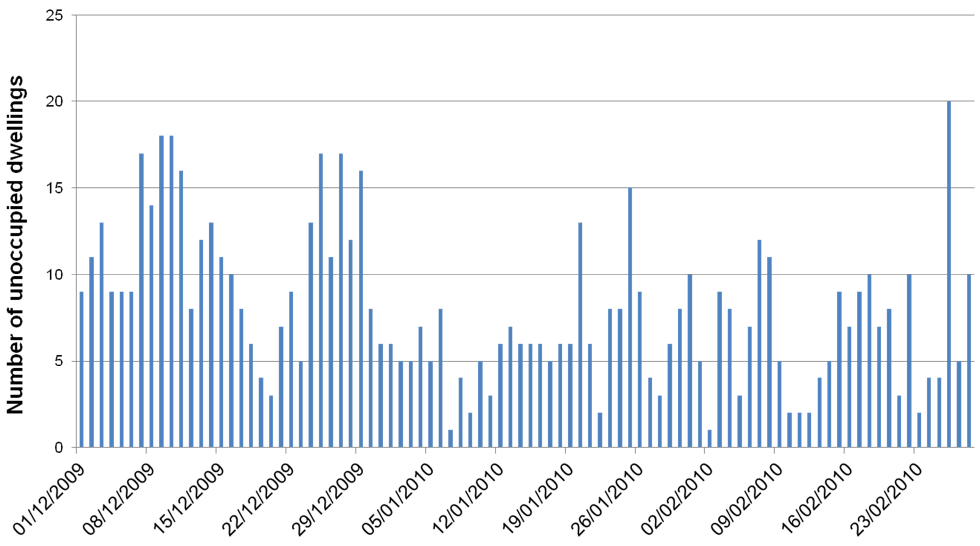


Figure 5-23. Number of under-heated dwellings on each day of the analysis period.

The author is unaware of any previous study which has reported number of under-heated days or an equivalent metric.

5.7 Summary

Household occupants use a variety of heating practices to maintain preferred indoor temperatures within their homes during winter periods. Hourly temperature data measured in 249 dwellings in Leicester has been used to calculate heating practice metrics one to five which provide an insight into how dwellings are heated. A summary of the heating practice metrics calculated are given according to a technical and social household descriptors (Table 5-4).

Table 5-4. Summary of results with reference to technical household descriptors showing average values and standard deviations, statistically significant results are shown in bold. All metrics are reported for the period December 2009 to February 2010 except threshold temperature where analysis was based on the period July 2009 to February 2010.

	Threshold temperature*	Under-heated days*	Daily heating period*	Heating pattern (no. of dwellings)		Single heating patterns** (from 80 homes)		Double heating patterns**			
No. of dwellings	229	249	191	249		80		111			
	(℃, SD)	(No. of days, SD)	(No. of hours, SD)	Sin gle	Double	On	Off	On	Off	On	Off
House type											
Detached	**14.0, 1.3**	2.3, 2.6	12.0, 3.9	8	15	07:00	23:00	07:00	09:30	15:00	22:00
Semi-detached	13.3, 1.3	2.4, 4.7	13.1, 3.6	46	56	07:00	23:00	06:00	09:00	15:00	22:00
End-terrace	13.6, 1.1	3.0, 4.6	11.9, 3.8	5	16	09:00	23:00	06:00	09:00	14:00	21:00
Mid-terrace	**12.9, 1.4**	3.4, 4.1	12.1, 3.1	15	29	08:00	21:00	06:00	10:00	15:00	22:00
Flat	13.3, 1.7	4.5, 4.2	12.6, 3.1	9	10	08:00	23:00	06:00	11:00	16:00	23:00
House age											
pre-1919	13.4, 1.5	3.3, 4.2	12.5, 3.7	11	28	07:00	23:00	07:00	09:00	15:00	23:00
1919-44	13.4, 1.2	2.0, 3.2	13.4, 3.4	30	34	07:00	22:00	06:00	09:00	13:30	22:00
1945-64	13.2, 1.4	3.2, 5.9	12.7, 3.3	22	31	07:00	22:00	06:00	10:00	15:00	22:00
1965-80	13.2, 1.3	2.7, 3.5	11.5, 3.4	10	17	08:00	23:00	06:00	09:00	16:00	22:00
post 1980	13.1, 1.8	3.8, 4.4	11.7, 3.8	10	16	08:00	23:00	06:00	09:00	16:00	23:00
Wall type											
Solid	13.3, 1.3	2.5, 3.8	13.0, 3.6	33	58	07:00	23:00	06:00	09:00	15:00	22:00
Cavity	13.2, 1.3	3.3, 3.8	12.2, 3.0	20	31	08:00	00:00	06:00	09:00	16:00	22:00
Filled cavity	13.3, 1.4	3.0, 5.3	12.4, 3.6	30	37	08:00	22:30	06:00	10:00	15:00	21:00

*Mean values reported **Median values reported

The threshold temperature which is the temperature below which households heat their homes was calculated as an indicator of the start of the heating season. 13℃ was the most common threshold temperature. All of the dwellings were heated at temperatures below 8℃ which occurred during November it was therefore concluded that during this monitoring period all of the dwellings were heated for the period December 2009 to February 2010. According to house type occupants living in mid-terrace dwellings have the lowest threshold temperatures (12.9℃) while occupants in detached dwellings have the highest (14.0℃) this result was found to be statistically significant (p=0.019). No statistically significant relationship was found between threshold temperature and the other technical and social household descriptors. The lowest threshold temperature was observed in the dwellings where the oldest occupants are between 20 and 30 years old (12.5℃). This suggests that younger occupants turn on their heating systems later in the year and therefore have shorter heating seasons than older occupants.

Threshold temperature was found to have a statistically significant relationship with mean winter temperature (p=0.001 & 0.021) and average maximum temperature (Metric 6) (p=0.000 & 0.006) in both living rooms and bedrooms. This suggests that the threshold temperature is related to thermostat setting i.e. a high thermostat setting may result in a high threshold temperature. The heating will turn on earlier in the year in dwellings with a higher thermostat setting resulting in a longer heating season as well as higher mean winter temperature.

Table 5-5. Summary of results with reference to social household descriptors, statistically significant results are shown in bold. All metrics are reported for the period December 2009 to February 2010 except threshold temperature where analysis was based on the period July 2009 to February 2010.

	Threshold temperature*	Under-heated days*	Daily heating period*	Heating pattern (no. of dwellings)		Single heating patterns**		Double heating patterns**			
No. of dwellings	229	249	191	249		80		111			
	(℃, SD)	(number of days, SD)	(number of days, SD)	Single	Double	On	Off	On	Off	On	Off
Tenure											
Own outright	13.5, 1.1	2.9, 5.2	13.3, 3.5	36	49	07:00	23:00	07:00	09:00	15:00	22:00
Mortgage	13.1, 1.2	2.7, 3.5	11.4, 3.6	17	47	08:00	22:30	06:00	09:00	15:00	22:00
Rent	13.2, 1.7	3.0, 4.0	13.0, 3.6	30	30	07:00	23:00	06:00	10:00	15:00	22:00
Employment status											
Employed	13.2, 1.4	3.0, 3.8	**11.7, 3.5**	25	82	08:00	23:00	06:00	09:00	15:00	22:00
Retired	13.3, 1.2	2.7, 5.7	13.7, 3.2	37	26	07:00	22:00	07:00	10:00	14:00	22:00
Unable to work	13.4, 1.6	2.4, 3.6	**14.0, 3.7**	11	6	06:00	23:00	06:00	09:00	14:30	22:30
Unemployed	12.8, 1.5	2.7, 3.3	12.3, 2.9	5	8	08:00	23:00	05:30	10:30	15:30	21:30
Other	13.8, 1.5	3.3, 4.3	14.6, 2.4	5	4	07:00	23:00	05:30	11:00	15:00	00:00
Age of oldest occupant											
20-29	12.5, 1.8	4.6, 4.6	12.1, 3.3	0	7	N/a	N/a	07:00	10:30	15:00	21:30
30-39	13.0, 1.6	3.3, 4.2	12.0, 4.4	12	23	07:00	23:00	06:00	09:00	15:00	23:00
40-49	13.2, 1.3	2.9, 3.3	**11.6, 3.4**	13	31	08:00	23:30	06:00	09:00	16:00	22:00
50-59	13.1, 1.0	2.5, 4.0	**11.6, 2.5**	10	23	07:30	23:00	06:00	09:00	15:00	22:00
60-69	13.5, 1.4	2.2, 3.5	**14.0, 3.0**	23	22	08:00	22:00	06:00	10:00	15:00	22:00
70+	13.6, 1.2	2.9, 6.3	13.6, 3.3	25	20	07:00	23:00	07:00	10:00	13:00	22:00
Household size											
1	13.2, 1.2	**5.0, 6.3**	12.5, 2.5	25	31	08:00	22:00	07:00	09:00	15:00	22:00
2	13.3, 1.3	1.9, 3.0	12.9, 4.1	31	47	07:00	23:00	06:00	09:00	16:00	22:00
3	13.4, 1.2	2.3, 3.6	12.2, 3.0	11	19	08:00	23:00	06:00	09:00	13:30	21:00
4	13.1, 1.9	2.7, 3.4	12.3, 4.0	11	18	07:00	22:30	06:00	09:00	15:00	22:00
5+	13.6, 1.4	**1.7, 1.8**	12.9, 3.3	5	11	06:30	23:30	05:30	10:00	15:00	22:30

*Mean values reported **Median values reported

The second heating metric was heating pattern. Double (51%) and single (33%) heating patterns dominated the sample. Double heating patterns are the predominant form of heating in most the technical and social categories. Single heating patterns are the most common in dwellings where the oldest occupant is 70 or more and where the household representative person (HRP) is retired or unemployed. In each of these categories it is expected that the household occupants would be in the house during the day and it is therefore not surprising that the single heating periods are more prevalent. Occupants living in flats were equally likely to use a single or double heating pattern.

The third heating metric was start and end times of heating. Dwellings where single and double heating patterns were observed were analysed. It was concluded that the calculation method used was most reliable in the dwellings with a single heating pattern. The start and end times calculated for single and double heating patterns suggested that dwellings with single heating patterns heat their homes for longer than those with who use two heating periods per day. Dwellings using a single heating pattern were also found to turn their heating on and off later than dwellings with a double heating pattern. Dwellings where the HRP was employed which used a double heating period had a first heating period which started and finished earlier than the other employment status groups.

The fourth heating metric was daily heating period which is an average measure of how long each heating system is in use per day. The longest average daily heating period was found in dwellings where the employment status of the HRP was 'other' (14.6 hours), dwellings where household representative (HRP) person was unable to work and where the oldest occupant was in their 60s also had long average daily heating periods (14.0 hours). A statistically significant relationship was identified with heating period according to employment status ($p=0.01$) and age of oldest occupant ($p=0.04$). Little difference can be observed in daily heating period across the different house type or age groups.

The fifth heating metric was number of under-heated days, which gives an insight to the consistency of heating in each dwelling. 39% of the dwellings had no unoccupied days and 17% dwellings only had 1 unoccupied day. 22% of the dwellings were unoccupied for between 2 and 4 days during the analysis period. 8% of dwellings have more than 10 or more under-heated days during the analysis period. Dwellings with a single occupant have the most under-heated days averaging five for the analysis period this was found to be statistically significant ($P<0.01$). This compares with only 1.7 for the dwellings with five or more occupants. Dwellings where the age of the oldest occupant is between 20 and 30 had more under-heated days than the other age ranges. This suggests that younger occupants living alone are the most likely to have inconsistent heating patterns and leave their homes unoccupied most frequently. The most under-heated days was found in a dwelling with a single occupant in the 70 years or older category and may be related to an extended stay in hospital or with family. As expected there were no statistically significant relationships established with number of under-heated days and technical house descriptors.

6 Heating practices – temperature

The final results chapter introduces the heating practice metrics which relate to temperature. Five heating practice metrics are described, the reasons why they are important explained, the calculation method shown and the results discussed.

The heating practice metrics in this chapter are not solely related to occupant behaviour but also give insight into the delivered temperatures of the heating systems in each dwelling. Although this work aims to explain the variation in how households heat their homes it is not always possible, first, to know which changes in indoor temperature relate to behaviour and which relate to the workings of the heating system and second, the impact of the efficiency and responsiveness of the heating system on how it is used by household occupants. It was therefore concluded that showing how indoor temperature during heated periods varies across the sample is important whether it is related to occupant behaviour, the characteristics of the heating system or the thermal efficiency of the building fabric. The five heating practice metrics discussed in this chapter are:

Table 6-1. Definitions of the heating practice metrics introduced in Chapter 6.

	Heating practice metric	Section	Definition
6)	Average maximum temperature	6.1	The average of the daily maximum temperature measured in living rooms
7)	Average temperature when heated	6.2	The average temperature between the start and end times of heating
8)	Time to reach peak temperature	6.3	The time between the start of each heating period and the time when the peak temperature (in that heating period) is reached
9)	ΔT_{peak}	6.4	The difference between the peak temperature reached in the first and second heating periods
10)	ΔT_{room}	6.5	The average temperature difference between living room and bedroom

In section 6.6 a summary of the main findings from the chapter is given and how the five heating practice metrics calculated in this chapter relate to a number of social and technical household descriptors is described.

6.1 Heating practice metric 6 – average maximum temperature

6.1.1 Calculating average maximum temperature

The sixth heating practice metric is average maximum temperature. Average maximum temperature was estimated by taking the mean value of the daily peak temperatures (maximum temperature observed for each day) for the analysis period (December 2009 and February 2010). As discussed in the previous chapter only living room temperature was considered as most room thermostats are situated downstairs and it was therefore assumed that the living room temperature would be more controlled. In Figure 6-1 the indoor temperature falls overnight, heating is turned on at 7:00am and the indoor temperature rises until 9:00am. The indoor temperature falls again until the second heating period which begins at 3:00pm after which the temperature increases until a peak temperature of 21.5℃ is reached at 10:00pm. The method to calculate average maximum temperature identifies the daily peak temperature for all days in each house during the analysis period and the mean value of the daily peaks is calculated. This method has been used in a previous temperature monitoring study to estimate thermostat setting (Shipworth et al., 2010).

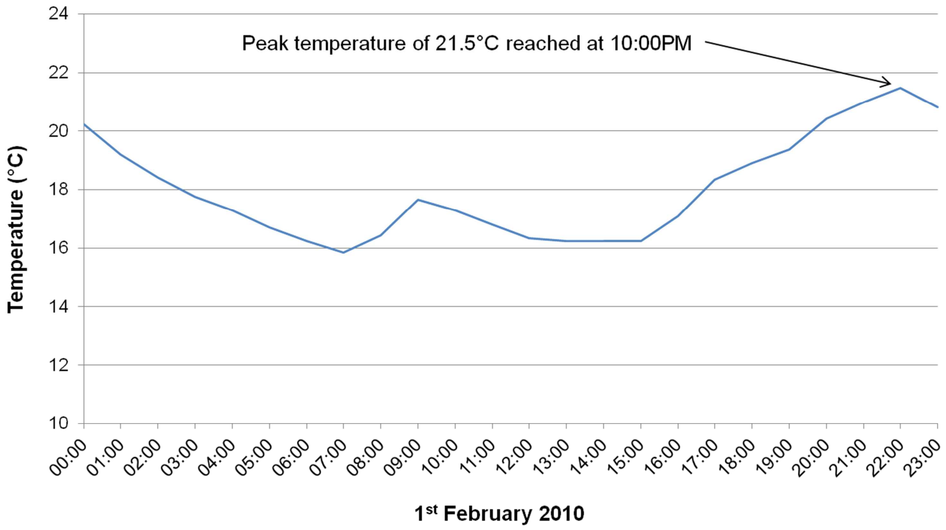


Figure 6-1. Living room temperature in a single dwelling measured on 1st February 2010 showing when the peak temperature is achieved.

Average maximum temperature will be a lower temperature than the thermostat setting (if placed in the living room) as it is an average for the whole period and therefore takes unoccupied periods into account. This method may also be affected by periods of high internal heat gain related to elevated occupancy levels or solar radiation.

6.1.2 Average maximum temperature results

The mean average maximum temperature across the 249 dwellings was 20.9°C (standard deviation 3.2°C) (Figure 6-2). The highest average maximum temperature was 30.5°C while the lowest was 11.0°C. The lowest average maximum temperature is partially related to this dwelling having 10 (11%) under-heated days, this dwelling is an end-terrace built between 1900 and 1919 and occupied by one person in their 20's. The highest average maximum temperature was measured in a detached dwelling built between 1966 and 1980, with 5 occupants and only 2 under-heated days.

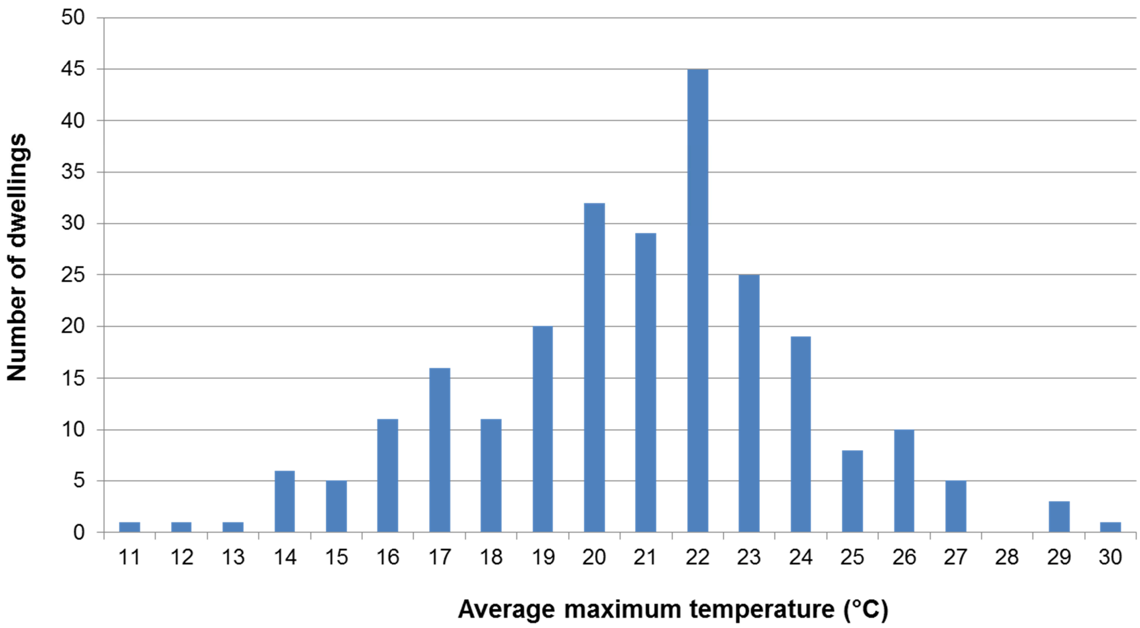


Figure 6-2. Histogram showing the average maximum temperature measured in 249 households in Leicester for the period December 2009 to February 2010.

16% of the living rooms had average maximum temperatures below 18℃ which is the world health organisation's recommended temperature for living spaces (WHO, 1985). Dwellings where very low average maximum temperatures were recorded have a high number of days where the dwelling was under-heated (heating practice metric 3) ($p<0.001$). Surprisingly, however, the significant difference occurred between those dwellings with none or one under-heated days and those with between 5 and 10 (average demand temperature 19.1℃) under-heated days ($q<0.01$) but not with the group with 10 or more under-heated days (20.2℃).

A similar method was used to calculate the 'estimated thermostat setting' in 195 dwellings by Shipworth et al. (2010). The mean estimated thermostat setting was 21.1℃ (standard deviation 2.5℃) which is within t he confidence interval of the average maximum temperature of 20.9℃ reported here but was found to be statistically different ($p>0.05$). The method used by Shipworth, however, did not count days when heating was not observed. The average maximum temperature calculated in the 96 dwellings with no under-heated days was 21.8℃ (standard deviation 2.8℃) which is a better comparison of th e method used by Shipworth and the two values were found to be statistically significant ($p=0.03$).

6.2 Heating practice metric 7 – average temperature when heated

6.2.1 Calculating average temperature when heated

The seventh heating practice metric 'average temperature when heated' and was calculated using the start and end times of heating as calculated in section 6.5. Ideally, average temperature when heated would be calculated on a day by day basis using a heating period derived for each day, however, as it was not possible to accurately identify start and end times of heating periods each day the average start and end times of heating were used.

The mean temperature at each hour of the day was calculated for all 249 dwellings, and the mean temperatures at each hour used to provide an average daily temperature profile. The average temperature between the start and the end times of heating was taken based on the average temperature profile. If the heating period started at 7:00am and ended at 5:00pm the mean temperature across the 11 hour period was calculated.

As start and end times of heating were calculated for the dwellings with single and double heating patterns it was only possible to calculate average temperature during heating periods for these dwellings. To ensure that results could be compared for the double heating group, only dwellings where start and end times of heating were available for both heating periods are reported.

As discussed earlier the method used to calculate the start and end times of heating is likely to result in longer heating periods in dwellings which are heated inconsistently. This will result in lower average temperatures when heated in these dwellings and especially in dwellings with short heating periods will reduce the accuracy of this metric.

It is noted that although this metric is called ‘average temperature when heated’ this calculation method includes some days when heating was not used.

6.2.2 Results of average temperature when heated

In the 80 dwellings with a single heating pattern the average temperature when heated was 18.2℃ (standard deviation 3.2℃) in liv ing rooms and 17.6℃ (standard deviation 3.4℃) in bedrooms. The lowest average temperature when heated in dwellings with a single heating pattern was 10.5℃ in a living room and 7.6℃ in a bedroom but these were not recorded in t he same dwelling.

The lowest average bedroom temperature was recorded in a semi-detached dwellings built between 1900 and 1919 occupied by one person in their 60s and there were four under-heated days. The lowest average living room temperature was measured in a detached dwelling built between 1920 and 1943 occupied again by one person in their 60s.

The highest average temperature in a dwelling with a single heating pattern was 25.7℃ for living rooms and 24.7℃ in bedrooms. The highest average living room temperature was recorded in a flat built since 1980 and occupied by one person who was over 70 years old. The average bedroom temperature in this dwelling was 23.6℃. Surprisingly, this dwelling had 10 under-heated days. The highest average bedroom temperature (24.7℃) was recorded in a detached dwelling built between 1920 and 1943 occupied by one period aged over 70. The average temperature during heating periods measured in the living room of this dwelling was 25.61℃.

The median average temperature when heated was 19℃ (23% of dwellings) and 16℃ (14% of dwellings) in living rooms and bedrooms respectively (Figure 6-3). The variation in average temperature when heated in dwellings with single heating patterns is greater in bedrooms than living rooms.

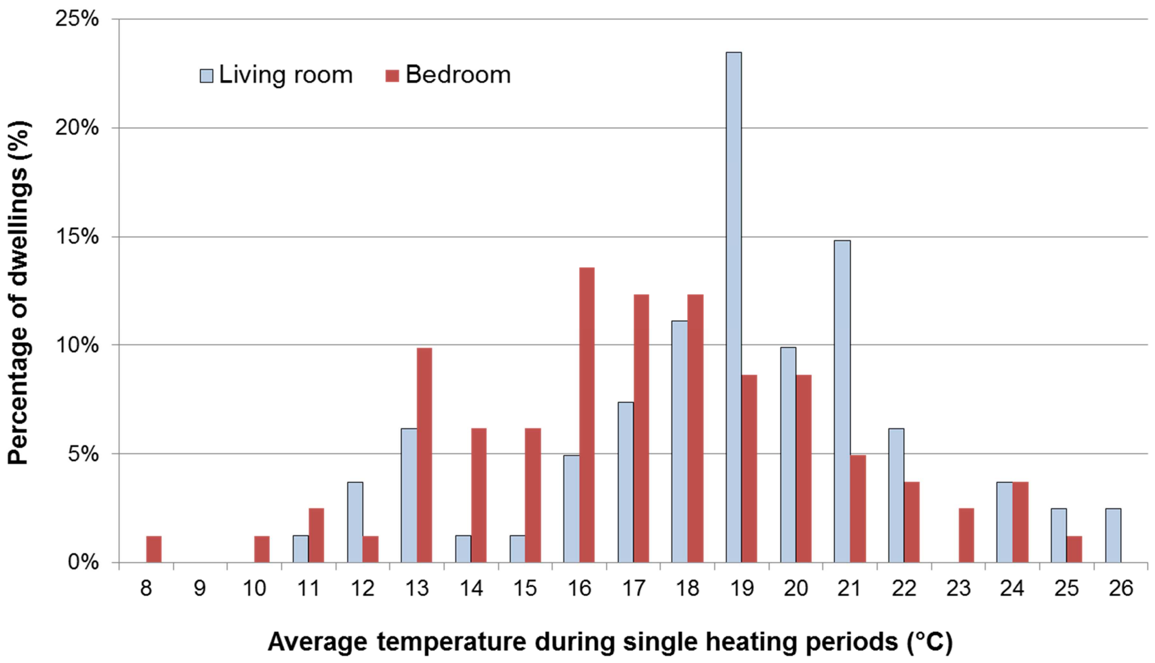


Figure 6-3. Histogram showing average temperature when heated in the 80 dwellings with a single heating pattern.

In the 111 dwellings with double heating periods average temperature when heated was 17.5℃ (standard deviation 2.8℃) in living rooms and 17.0℃ (standard deviation 2.7℃) in bedrooms in the first heating period and 19.0℃ (standard deviation 3.0℃) and 17.8℃ (standard deviation 2.8℃) in the second heating period in living rooms and bedrooms respectively. The difference between the average temperatures across the two heating periods measured in bedrooms is less than in living rooms.

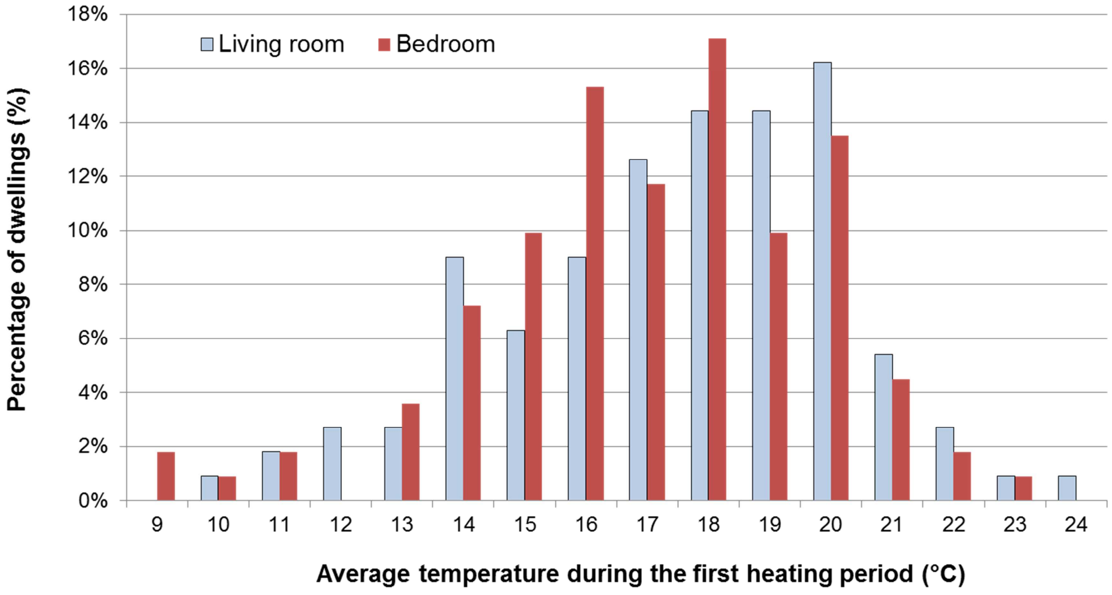


Figure 6-4. Histogram showing average temperature when heated for the first heating period in the 111 dwellings with a double heating pattern.

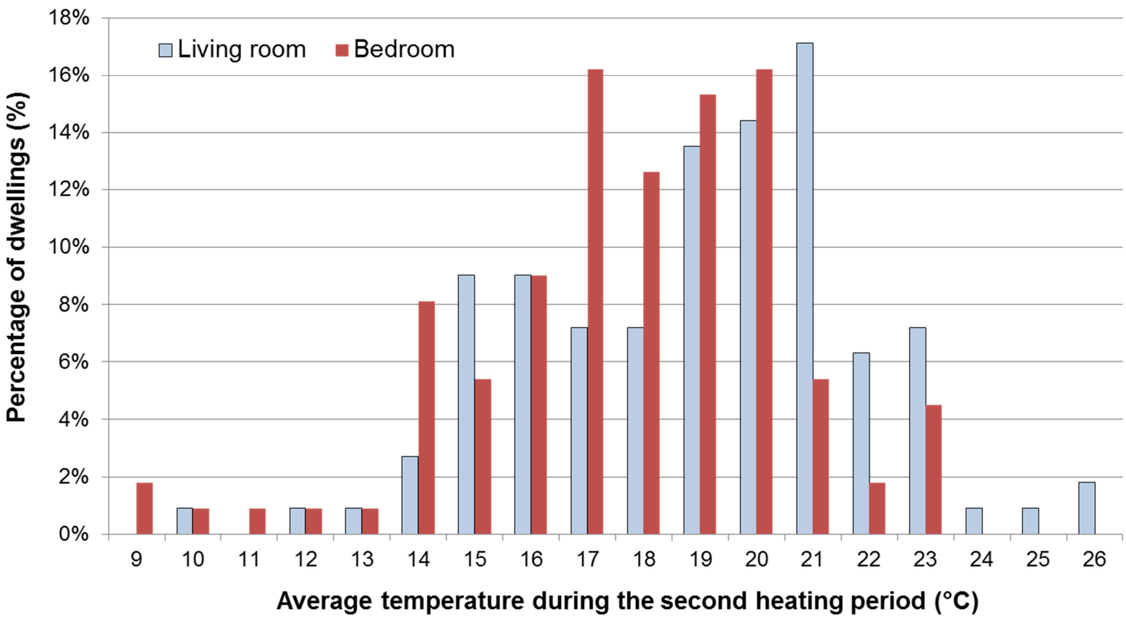


Figure 6-5. Histogram showing average temperature during the second heating period in the 111 dwellings with a double heating pattern.

The highest average temperatures in dwellings with a double heating pattern, in living rooms and bedrooms respectively, were 24.1℃ and 22.5℃ in the first heating periods and 25.7℃ and 23.5℃ in the second heating period. The dwelling with the highest living room temperature measured during the first heating period also had the highest temperature in the second heating period. This dwelling was an end-terrace built between 1966 and 1980 occupied by two people; the age of the oldest occupant is over 70. The dwelling with the highest bedroom temperatures recorded in the first and second heating period was also the same dwelling, the dwelling was an end-terrace built between 1966 and 1980 occupied by 5 or more people; the age of the oldest occupant is in their 40s.

The lowest average temperatures measured in the first heating period in dwellings with a double heating pattern were 9.7℃ and 9.3℃, in a living room and bedroom respectively. In the second heating period the average temperatures were 9.9℃ and 9.3℃ respectively. The low temperatures measur ed in the living room during the first and second heating period were from the same dwelling, an end-terrace built between 1900 and 1919 occupied by one person in the 20s, this dwelling was under-heated for 10 days during the heating season. The average temperatures when heated measured in bedrooms in this dwelling were slightly warmer than in the living room and were 10.6℃ and 10.9℃ for the first and second heating period respectively. The low average temperatures measured in a bedroom were also from the same dwelling which was an end-terrace built between 1944 and 1965 occupied by one person over 70 years old. The average temperatures when heated is in the living room of this dwelling were 13.5℃ and 14.7℃.

The median average temperatures were 20℃ (16% of d wellings) and 18℃ (17% of dwellings) during the first heating period and 21℃ (17% of dwellings) and 17℃ (16% of dwellings) during the second heating period, in living rooms and bedrooms respectively.

The author is unaware of other studies that have reported average temperatures when heated; however, it is possible to compare these findings with the thermostat set points use in SAP. In living rooms SAP uses a demand temperature of 21℃, this is higher than the average temperature when heated reported here for all three heating periods (i.e. single and both double). For bedrooms SAP lowers the temperature depending on the heat loss parameter of the dwelling (DECC, 2011c). In a dwelling without thermostatic control (like the majority the dwellings in this sample) the bedroom temperature is given by the following equation

$$Bedroom\ temperature = 21 - 0.5\ \times Heat\ loss\ parameter \qquad \text{[Equation 6-1]}$$

Heat loss parameter is a function of a dwelling's heat loss co-efficient and total floor area. Average heat loss co-efficient and total floor area in UK dwellings are 247 W/K and 82.2m^2 (Firth & Lomas, 2009) and therefore a typical heat loss parameter for a UK dwelling is 3 W/m^{2}K. In a dwelling without thermostatic control this results in a bedroom temperature during heating periods of 19.5°C. This is again higher than the average temperatures calculated for the heating periods in this chapter.

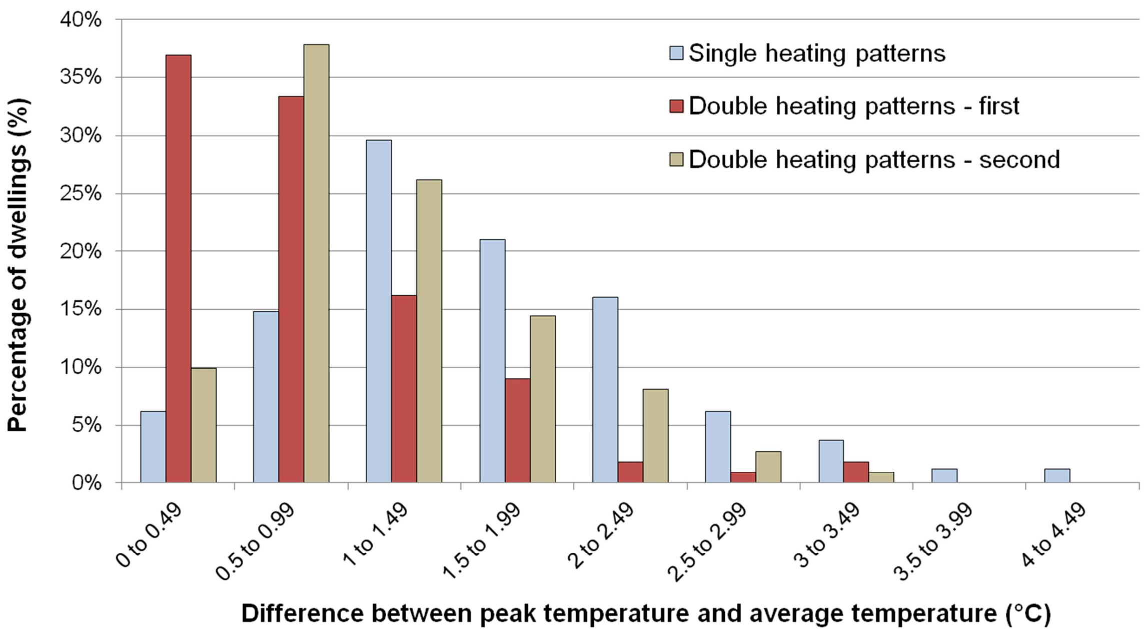


Figure 6-6. Histogram showing difference between peak temperature and average temperature when heated in living rooms.

The fact that actual temperatures measured in heating periods are lower than those suggested in energy models is possibly related to the time it takes for the demand temperature to be reached in the dwellings. To test this average living room temperature during heating periods was subtracted from the peak temperature measured during the heating period (this is the same as Metric 6 for dwellings with a single heating pattern) to give an indication of how controlled the temperatures are during heating periods. This is plotted for all three heating patterns discussed here (Figure 6-6). The greatest difference between peak and average temperatures occurred in dwellings with single heating patterns. This is because that the indoor temperature tends to increase until the peak temperature is reached at the end of the heating period. Consequently, longer heating periods result in a greater temperature difference between the average and peak temperatures measured in a heating periods. The shortest heating periods are seen in the first heating period in dwellings with double heating periods, during these heating periods the difference between peak and average temperature is very low as there is not enough time for the temperature to rise. These results bring in to question the temperature profiles used in BREDEM-based models which assume that the demand temperature is maintained during the whole of the heating period.

6.3 Heating practice metric 8 – time to reach peak temperature

6.3.1 Calculating time to reach peak temperature

The eighth heating practice metric is time to reach peak temperature. This metric was designed to gain insight into the responsiveness of heating systems and the extent of thermostatic control in dwellings. It is also an insight into the validity of the idealised temperature profile used in BREDEM which assumes that peak temperature is reached at the start of the heating period and then maintained until the heating period ends.

For this calculation the average daily temperature profile of each dwelling was used. The start times of the heating periods as calculated in section 6.5 were again used. The time of the average peak (maximum) temperature in each dwelling with a single or double heating pattern was identified based on the average temperature profile or each dwelling (Figure 6-7). The time to reach peak temperature was calculated by subtracting the time when the peak temperature was reached from the start time of heating period. In dwellings with double heating patterns the time to reach peak temperature was calculated for both of the heating periods.

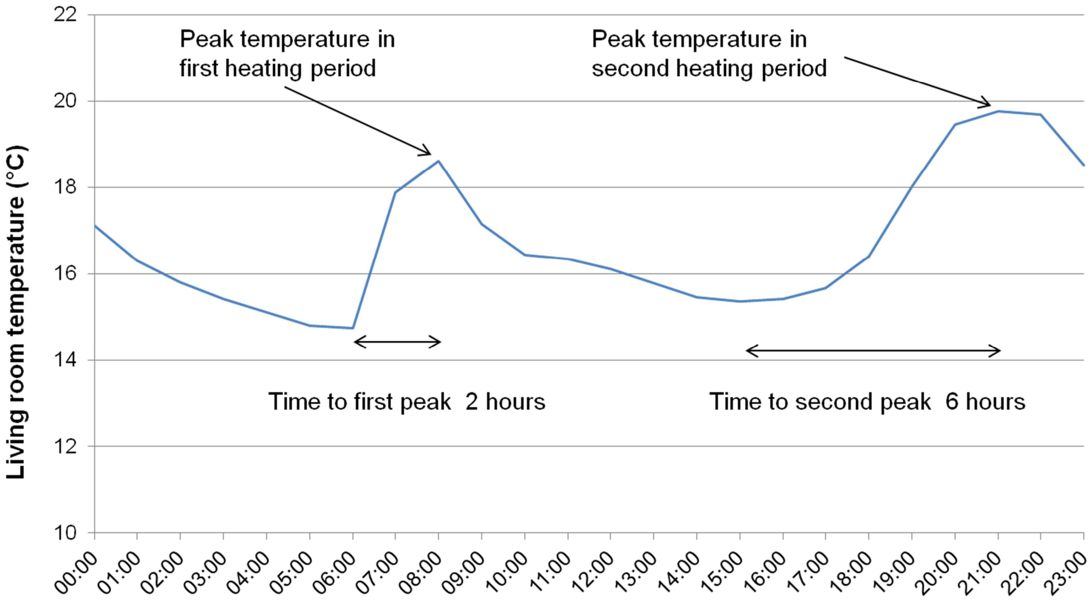


Figure 6-7. Average daily temperature profile (December 2009 – February 2012) for a single dwelling showing method of identifying the time to reach peak temperature.

A limitation of this method is related to the use of the average daily temperature profile for calculating the time of peak temperature. An ideal method would calculate the time to reach peak temperature each day and then average for the whole winter period, as it was not possible, however, to accurately calculate the start and end times of heating periods on daily basis this was not possible. The method used here, however, is not expected to produce significantly different results than a method calculated on a daily basis. As the heating practice metrics discussed in this work aim to gain insight into the variation of average heating practices over the whole sample and identify any trends across different household descriptors using the time of average peak temperatures was deemed to be a reasonable compromise.

The use of an average temperature profile does have an advantage over a method that is based on calculating the time to reach peak temperature on a daily basis as it reduces the error related to boiler cycling. It is unlikely that the cycling of the boiler would occur at the same time each day and therefore over the 90 day analysis period the subtle changes in indoor temperature related to boiler cycling will be smoothed out.

6.3.2 Results of time to reach peak temperature

This section describes the results of time to reach peak temperature for dwellings with single heating periods and for both heating periods in dwellings with double heating patterns.

The longest times to reach peak temperature were found in the dwellings with single heating periods. The median time to reach peak temperature was 15 hours, 3 hours and 7 hours in single, first and second heating periods respectively. The longest time to reach peak temperature was 22 hours. This occurred in a detached dwelling built between 1900 and 1919 occupied by two occupants, the oldest occupant was over 70 years old. The shortest time to reach peak temperature in a dwelling with a single heating pattern was 6 hours, this occurred in mid-terrace built between 1944 and 1965 occupied by two people one of whom was in their 60s.

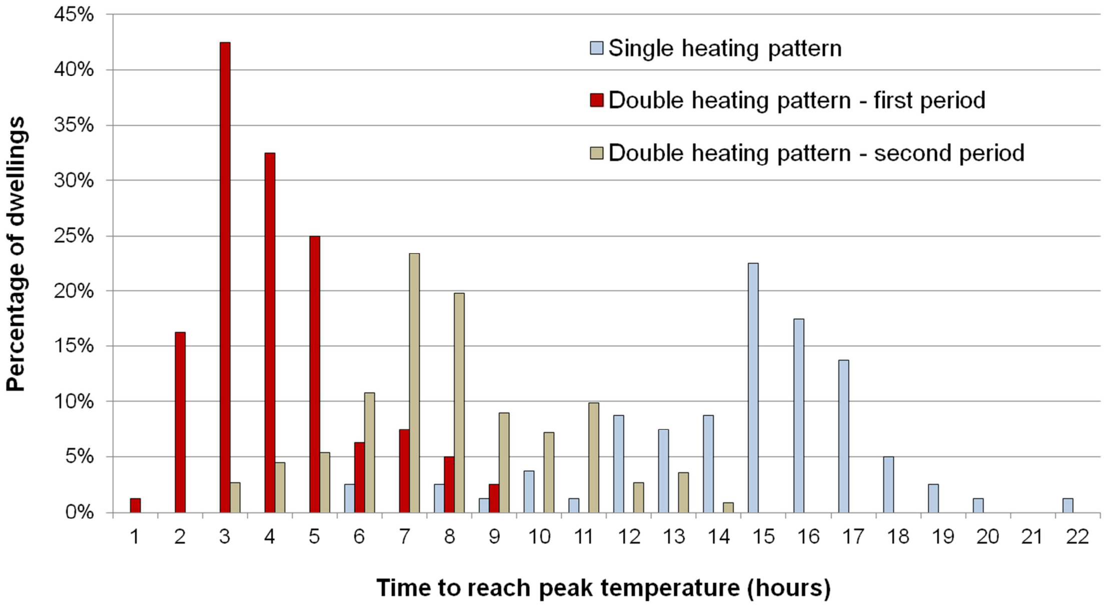


Figure 6-8. Histogram showing time to reach peak temperature in dwellings the 80 dwellings with single and 111 dwellings with double heating patterns.

In dwellings with a double heating pattern the median time to reach peak temperature was 3 hours for the first heating period and 7 hours for the second heating period. The shortest times to reach peak temperature were 1 hours and 3 hours for the first and second heating periods respectively. The longest times to reach peak temperature were 9 and 14 hours for the first and second heating periods respectively.

The percentage of the duration of heating period before peak temperature was reached was calculated for each dwelling. For single, first and second heating periods the peak temperature was reached at the end of the heating period in 74%, 87% and 94% of the dwellings respectively. The peak temperature was recorded at the end of the heating period in most cases and consequently dwellings do not reach peak temperature early in the heating period and maintain this temperature as suggested in the idealised temperature profile used in BREDEM.

Dwellings with a single heating pattern have on average the longest heating periods, in these 26% of these dwellings peak temperature is reached before the end of the heating period. In dwellings with on average two shorter heating periods the peak temperature is more likely to be reached at the end of the heating periods. This could be because dwellings take some time to warm up to the thermostat setting.

6.4 Heating practice metric 9 – ΔT_{peak}

6.4.1 Calculating ΔT_{peak}

As shown in section 6.3 the peak temperature is reached at the end of the heating period in most dwellings. This may lead to longer heating periods having higher average temperatures. It is also of interest to understand whether, in dwellings with double heating patterns, both heating periods have similar peak temperatures. To explore these things further the ninth heating practice metric 'ΔT_{peak}', which is the difference in peak temperature reached in the first and second heating periods, was calculated. This is important as BREDEM assumes that the indoor temperatures reached are the same during both heating patterns.

ΔT_{peak} is illustrated in Figure 6-9. Temperature decreases overnight, at 8:00am heating is turned on and temperature increases until the peak temperature during the first heating period is reached at 10:00am ($T_{1st\ peak}$). Temperature falls slightly until the start of the second heating period, the peak temperature during the second heating period is reached at 10:00pm ($T_{2nd\ peak}$). In the example below $T_{1st\ peak}$ is lower than $T_{2nd\ peak}$.

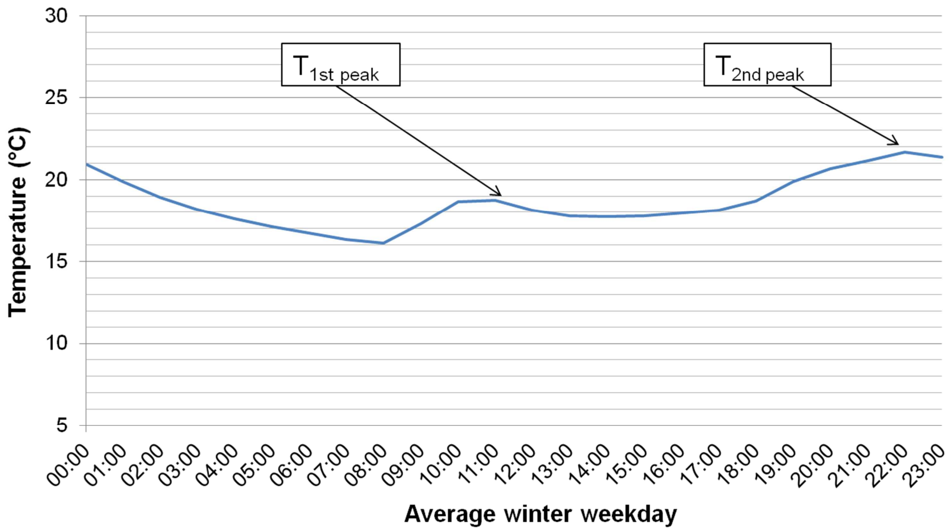


Figure 6-9. Average winter weekday in a single living room showing a double heating period with morning and evening peaks.

ΔT_{peak} was calculated using the average daily temperature profile. The start and end times of the heating periods were used and the maximum temperature in each heating period identified. To calculate ΔT_{peak} the peak temperature reached during the first heating period was subtracted from the peak temperature reached during the second heating period.

As discussed in the previous section ideally ΔT_{peak} would be calculated on a daily basis but this was not possible as the start and end times could not be identified on a day by day basis.

6.4.2 Results of ΔT_{peak}

ΔT_{peak} measured in living room spaces of the 111 dwellings with double heating patterns are shown in Figure 6-10. The average ΔT_{peak} was 1.9℃ (standard deviation 1.4℃). Only 3 dwellings had higher peak temperature in during the first heating period. This is probably a result of the second heating period generally being longer than the first heating period and the fact that most of the peak temperatures occur towards the end of the heating period.

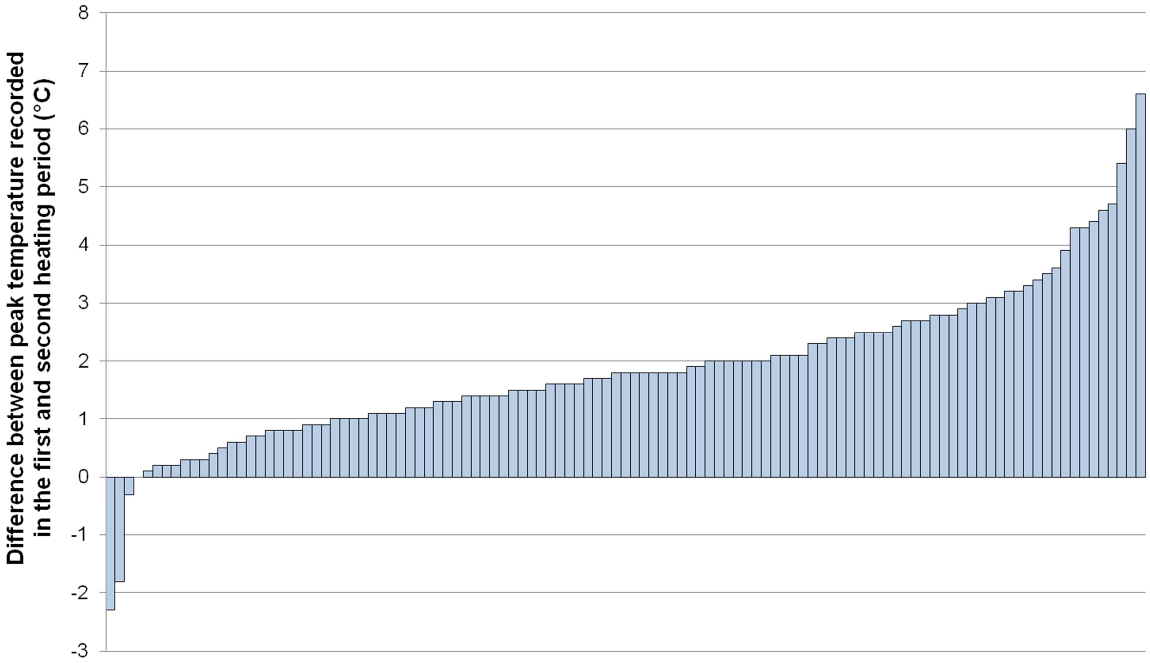


Figure 6-10. ΔT_{peak} (difference between peak temperature recorded in the first and second heating period) in 111 dwellings with a double heating period.

The highest and lowest ΔT_{peak} were 6.6℃ and -2.3℃ respectively. The highest ΔT_{peak} occurred in a mid-terrace built between 1920 and 1943 occupied by four people with the oldest occupant being in their 40s. The lowest ΔT_{peak} (where the peak temperature was higher in the first heating period) occurred in a mid-terrace built between 1920 and 1943 occupied by two people the oldest being in their 60s.

In the morning household occupants are likely to be active and they may therefore not require indoor temperatures as high as they would in the evening when they may be sitting inactive for long periods. The consequence of this may be that occupants actively increase the temperature in living rooms during evening periods by using secondary heat sources or increasing the thermostat temperature.

6.5 Heating practice metric 10 – ΔT_{room}

6.5.1 Calculation of ΔT_{room}

The tenth and final heating practice metric is ΔT_{room} which is the average difference between living room and bedroom temperature. ΔT_{room} is an insight into the variation in temperature throughout the dwelling. This heating practice metric is important as BREDEM-based models assume that the living room is part of zone 1 which is heated to a higher temperature than zone 2 which incorporates the bedroom.

ΔT_{room} was calculated for all 249 dwellings by subtracting the bedroom temperature at each hour from the living room temperature and then taking the average difference for the analysis period (December 2009 – February 2010).

6.5.2 Results of ΔT_{room}

The mean ΔT_{room} was 1.0℃ (standard deviation 2.5℃). The lowest ΔT_{room} -6.1℃, which means that the bedroom was on average 6℃ war mer than the living room, this occurred in a detached dwelling built since 1980 with 3 occupants. The highest ΔT_{room} was 8.8℃, meaning that the living room was on ave rage nearly 9℃ warmer than the bedroom, this occurred in a semi-detached dwelling with central heating built 1944 and 1965 with 4 occupants.

In all, 68% of households have warmer living rooms than bedrooms (Figure 6-11). It is assumed that living room temperatures are higher on average because more time is spent in these by household occupants. As temperature was only measured in two of the rooms it is not possible to assess the variation of temperature throughout the whole dwelling using this sample.

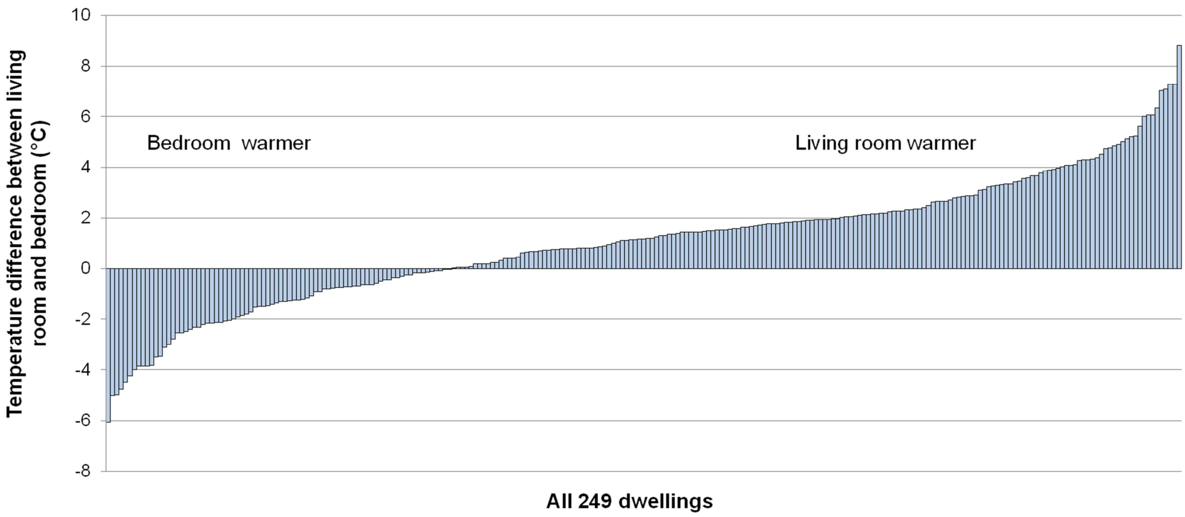


Figure 6-11. Temperature difference between living room and bedroom (ΔT_{room}) measured in 249 dwellings in Leicester.

ΔT_{room} is related to whether or not dwellings have central heating ($p=0.003$). Average temperature difference between living room and bedroom is 0.9℃ in dwellings with central heating but 2.8℃ with no central heating. This trend was also found in New Zealand homes (French et al., 2007).

There are a number of heating practices that occupants can use to maintain a higher temperature in a particular part of the house. These include the use of secondary heating, thermostatic radiator values (TRVs) and opening and closing of curtains, windows and internal doors. There is also likely to be significant variation in heat loss in different parts of the dwelling due to deviation of both thermal transmittance and infiltration.

6.6 Summary

Household occupants use a variety of heating practices to control the indoor temperature within their homes. This chapter has examined heating practice metrics six to ten, based on analysis of hourly temperature data collected in 249 dwellings in Leicester city, which relate to the indoor temperatures.

Three of the heating practices discussed in this chapter use a profile approach based on the average temperature at each hour of the day across the heating period. The profile approach allows for comparison of average heating practices over the whole of the heating season across the sample, but does not tell the whole story of how occupant behaviour changes during the heating season in individual dwellings. For example, in a dwelling with a large number of under-heated days the average temperature when heated will be reduced as a number of days when the dwelling was not heated will be included in the averaging process. It would be possible to calculate the temperature metrics discussed in this chapter based on the days when heating was used but to enable comparison with model assumptions this work aims to give an insight into average heating practices across the whole heating season and identify any trends which relate to technical and social household descriptors. When results for one heating practice metric may have been impacted by another heating practice metric this has been highlighted.

The sixth heating metric was average maximum temperature which is an indication of the temperature to which occupant's heat their homes. The average maximum temperature was 20.9℃. The average maximum tempera ture reported here is similar to those reported in previous studies and to the demand temperature used in BREDEM-based models. A large variation in average maximum temperature across the sample, however, was shown; the highest average maximum temperature was 30.5℃ while the lowest was 11.0℃. According to house type, the highest average maximum temperatures were found in flats (22.3℃) and the lowest in mid terraced dwellings (20.2℃), this was not found to be a statistically significant difference (P>0.05). Dwellings where the oldest occupant was in their twenties had low average maximum temperatures (18.3℃) this is partially related to these dwellings having the highest number of under-heated days. The relationship between average maximum temperature and age of oldest occupant was found to be statistically significant (p=0.015) with the significant differences occurring between the 20-29 group and the 60-69 group (q=0.013) and 70+ group (q=0.019). The highest average maximum temperatures were recorded in dwellings where the Household Representative Person (HRP) was permanently unable to work (22.7℃) this was found to be statis tically different from the average maximum temperature calculated for dwellings where the HRP was employed (q=0.017). The clearest trend can be observed in the house age descriptor (p=0.020) the lowest average demand temperatures are seen in the oldest dwellings built before 1919 (19.6℃) and average ma ximum temperature increases as the dwellings are newer, dwellings built between 1965 and 1980 have the highest demand temperature (21.9℃), average demand temperature falls again in the newest dwellings built since 1980 (21.0℃) (a s imilar trend as seen before with mean winter temperature). A statistically significant difference was also observed between average maximum temperatures recorded in dwellings which were owned with the aid of a mortgage (20.1℃) and those that were rented (21.6℃) (q=0.011).

The seventh heating practice metric was average temperature when heated. This was calculated for dwellings with single heating patterns and for both heating periods in dwellings with double heating patterns. The average temperatures during single heating periods were 18.2℃ in living rooms and 17.6℃ in bedrooms. In dwellings with double heating patterns average temperatures during the first heating period were 17.5℃ and 17.0℃, in living ro oms and bedrooms respectively, in the first heating period average temperatures were 19.0℃ and 17.8℃ in living rooms and bedrooms respectively. A verage temperatures in dwellings with a double heating pattern were higher in the second heating period; this is most likely a result of the second heating period being longer than the first.

Table 6-2. Table showing the variation of heating metrics 6 – 10 according to technical household descriptors, statistically significant results are shown in bold.

	Average maximum temperature	Average temperature when heated (living room) (mean ℃, SD)			Average temperature when heated (bedroom) (mean ℃, SD)			Time to reach peak temp (hours)			ΔT_{peak}	ΔT_{room}
	(mean ℃, SD)*	Single**	Double – first***	Double – second***	Single**	Double – first***	Double – second***	Single**	Double – first***	Double – second***	(mean ℃, SD)***	(mean ℃, SD)*
House type												
Detached	20.4, 3.9	18.3, 4.3	15.7, 2.3	17.6, 2.4	17.0, 4.2	16.3, 2.4	17.4, 2.1	**14.9, 4.1**	3.6, 1.1	7.6, 2.2	2.2, 1.4	0.3, 2.6
Semi-detached	21.1, 3.0	19.0, 2.9	17.6, 2.6	19.3, 2.9	16.7, 3.6	17.0, 2.5	17.8, 2.5	**15.4, 2.1**	**3.8, 1.3**	8.3, 2.3	2.1, 1.3	1.5, 2.5
End-terrace	21.0, 3.4	17.4, 2.6	17.8, 3.4	19.5, 3.8	17.4, 2.9	17.1, 3.4	17.8, 3.6	13.2, 3.4	4.1, 1.6	7.4, 1.7	1.9, 1.0	0.7, 2.5
Mid-terrace	20.2, 3.1	17.9, 3.8	17.1, 2.4	18.3, 2.6	17.6, 3.3	17.0, 2.5	17.5, 2.7	13.5, 3.8	4.3, 2.0	8.0, 2.7	1.7, 1.6	0.5, 2.5
Flat	22.3, 3.5	20.5, 3.2	19.2, 3.1	20.3, 3.5	18.6, 2.5	18.2, 3.5	18.9, 4.0	**12.8, 2.6**	**5.9, 1.9**	7.3, 2.9	0.6, 1.0	1.5, 1.8
House age												
pre-1919	**19.6, 3.7**	16.9, 3.5	16.5, 3.2	17.9, 3.5	16.0, 3.8	16.5, 3.2	17.1, 3.4	16.2, 2.6	3.8, 1.5	8.3, 2.2	1.8, 1.3	0.6, 2.8
1919-44	20.7, 3.0	18.7, 3.1	17.5, 2.4	19.0, 2.4	16.6, 3.7	17.3, 2.1	18.2, 2.1	14.4, 3.0	4.4, 1.8	8.6, 2.6	1.9, 1.6	1.0, 2.4
1945-64	**21.5, 3.5**	20.1, 3.3	17.5, 2.9	19.3, 3.3	18.2, 3.0	16.3, 2.9	17.2, 3.1	14.8, 2.8	4.2, 1.6	7.4, 2.4	2.0, 1.4	1.6, 2.6
1965-80	**21.9, 2.6**	18.9, 1.5	18.9, 2.5	20.4, 2.6	17.3, 2.8	18.1, 2.5	19.0, 2.5	14.7, 1.9	3.9, 1.4	7.3, 2.2	2.1, 1.0	1.2, 2.2
post 1980	21.0, 2.7	18.4, 3.5	17.5, 2.2	19.0, 2.6	17.7, 3.5	17.6, 2.1	18.0, 2.0	13.0, 3.7	4.2, 2.0	7.5, 1.9	1.4, 1.3	0.7, 2.2
Wall type												
Solid	20.4, 3.2	17.9, 3.1	17.1, 2.9	18.5, 2.9	16.6, 3.2	17.2, 2.5	17.9, 2.7	15.5, 2.7	4.0, 1.6	8.4, 2.2	1.8, 1.4	0.6, 2.5
Cavity	20.8, 3.6	19.5, 4.0	17.5, 3.1	19.0, 3.4	17.7, 4.2	16.3, 3.2	17.3, 3.5	13.8, 2.5	4.3, 1.6	7.7, 2.5	1.8, 1.4	1.2, 2.5
Filled cavity	21.6, 2.9	19.4, 2.7	18.1, 2.2	19.9, 2.7	17.4, 3.2	17.3, 2.4	17.9, 2.4	14.2, 3.2	4.1, 1.7	7.4, 2.3	2.0, 1.3	1.5, 2.4

* based on all 249 dwellings
** based on 80 dwellings with single heating patterns
*** based on 111 dwellings with double heating patterns

Although a number of trends similar to those found for mean winter temperature and average maximum temperature can be observed. No statistically significant relationship was found for average temperature when heated and the technical house descriptors. A number of statistically significant relationships were found, however, with average temperature when heated and the social descriptors. Household size was found to have a statistically significant relationship with average temperature during single heating periods ($p=0.025$) but not for double heating periods ($p=0.392$ & $p=0.576$). Low average temperatures during all types of heating period were found in dwellings with only one occupant, this is probably related to the high number of under-heated days which were seen in these dwellings. Employment status was found to have a statistically significant relationship with average temperature when heated in dwellings with double heating patterns ($p=0.038$ & 0.043) but not for those with a single heating pattern ($p=0.079$). The significant difference was observed between the employed (first 17.0℃, second 18.5℃) and the unable to work group s (first 20.4℃, second 22.1℃) ($q=0.048$).

The most significant trend observed was in the age of oldest occupant descriptor, in living rooms during both heating periods the lowest average temperatures when heated are found in the dwellings where the age of the oldest occupant is between 20 and 30. Average temperature when heated increases with each age band in both heating periods. Dwellings where the age of the oldest occupant is in the 20-30 group had particularly low average temperatures during the first (13.9℃) and second heating periods (14.8℃) in dwellings with d ouble heating patterns (no single heating patterns were found in this group) these temperatures were significantly different to all other groups ($q<0.05$). This result is possibly related to the high proportion of under-heated days in dwellings where the oldest occupant is in their 20's.

The average temperature in the second heating period was higher than the average temperature in the first heating period across all technical and social descriptors. This suggests that the idealised temperature profile used in the standard assessment procedure which assumes that temperature is remains constant during and across different heating patterns is incorrect.

Table 6-3. Table showing the variation of heating metrics 6 – 10 according to social household descriptors, statistically significant results are shown in bold.

	Average maximum temperature	Average temperature during heated period (living room) (℃, SD)			Average temperature during heated period (bedroom) (℃, SD)			Time to reach peak temp. (hours)			ΔT_{peak}	ΔT_{room}
	(℃, SD)*	Single**	Double – first***	Double – second***	Single**	Double – first***	Double – second***	Single**	Double – first***	Double – second***	(℃, SD)***	(℃, SD)*
Tenure												
Own outright	21.1, 3.0	17.5, 3.0	17.0, 2.7	18.5, 2.9	17.0, 3.2	17.0, 2.7	17.8, 2.8	14.3, 3.1	3.8, 1.5	7.9, 2.1	2.1, 1.2	0.4, 2.4
Mortgage	**20.1, 3.4**	19.0, 3.3	18.5, 2.7	20.1, 3.0	17.2, 3.9	16.6, 2.9	17.1, 3.2	14.4, 3.2	4.5, 2.0	8.1, 2.7	1.8, 1.6	1.9, 2.3
Rent	**21.6, 3.2**	20.7, 2.6	20.4, 2.6	22.1, 3.5	18.2, 3.4	19.1, 1.9	19.9, 1.9	15.7, 2.1	4.0, 1.4	8.0, 3.6	1.6, 1.2	2.0, 2.9
Employment status												
Employed	**20.4, 3.2**	17.5, 3.0	**17.0, 2.7**	**18.5, 2.9**	17.0, 3.2	17.0, 2.7	17.8, 2.8	14.3, 3.1	**3.8, 1.5**	7.9, 2.1	2.1, 1.2	**0.4, 2.4**
Retired	21.4, 3.2	19.0, 3.3	18.5, 2.7	20.1, 3.0	17.2, 3.9	16.6, 2.9	17.1, 3.2	14.4, 3.2	4.5, 2.0	8.1, 2.7	1.8, 1.6	**1.9, 2.3**
Unable to work	**22.7, 2.8**	20.7, 2.6	**20.4, 2.6**	**22.1, 3.5**	18.2, 3.4	19.1, 1.9	19.9, 1.9	15.7, 2.1	4.0, 1.4	8.0, 3.6	1.6, 1.2	2.0, 2.9
Unemployed	20.6, 3.5	19.6, 3.4	17.1, 2.6	18.4, 2.8	15.7, 1.6	17.2, 2.2	18.0, 2.0	14.2, 2.4	4.8, 1.7	7.8, 3.6	0.7, 1.5	1.3, 2.9
Other	20.9, 2.5	18.4, 3.0	18.0, 2.8	19.3, 2.7	17.2, 1.8	17.7, 1.4	18.6, 1.5	15.6, 2.1	**6.0, 1.8**	9.0, 1.6	1.1, 1.0	1.0, 2.0
Age of oldest occupant												
20-29	**18.3, 3.5**	n/a, n/a,	**13.9, 2.6**	**14.8, 2.6**	n/a, n/a	13.7, 2.6	14.5, 2.5	n/a, n/a	4.0, 1.5	8.3, 2.8	1.1, 1.1	**0.0, 1.7**
30-39	20.6, 3.5	18.3, 3.3	17.5, 2.4	18.9, 2.6	17.7, 1.7	17.2, 2.5	17.8, 2.7	14.7, 4.1	4.0, 1.8	8.0, 2.3	1.6, 0.8	0.6, 2.4
40-49	20.6, 3.1	18.2, 3.1	16.9, 2.7	18.5, 3.1	16.0, 3.3	17.6, 2.3	18.5, 2.4	15.1, 1.4	3.9, 1.6	7.4, 2.3	2.1, 1.5	0.5, 2.5
50-59	20.7, 3.1	18.2, 4.0	17.5, 2.6	19.1, 2.4	16.1, 2.9	17.2, 2.8	18.1, 2.8	14.2, 2.3	4.0, 1.4	8.4, 2.1	1.9, 1.4	0.9, 2.6
60-69	**21.7, 2.7**	19.2, 3.0	**18.8, 2.1**	**20.3, 2.2**	17.5, 3.8	17.4, 2.3	18.1, 2.5	14.3, 3.0	4.7, 2.1	7.8, 2.5	1.8, 1.6	1.5, 2.4
70+	**21.6, 3.4**	19.3, 3.2	**18.4, 3.1**	**20.3, 3.5**	17.6, 3.9	16.4, 3.0	17.0, 3.3	14.8, 3.2	4.1, 1.5	8.2, 2.6	2.1, 1.3	**2.0, 2.5**
Household size												
1	20.2, 3.8	**17.3, 4.0**	16.9, 3.2	18.3, 3.6	**15.8, 4.0**	15.9, 3.3	16.5, 3.6	13.8, 2.4	4.0, 1.4	8.1, 2.4	1.6, 1.4	1.1, 2.4
2	21.3, 2.8	19.9, 2.2	17.8, 2.8	19.3, 3.0	**18.7, 3.1**	17.2, 2.3	17.8, 2.2	15.0, 3.6	4.2, 1.7	8.0, 2.4	1.9, 1.4	1.1, 2.4
3	20.8, 3.3	18.2, 3.6	17.2, 2.1	18.9, 2.4	15.7, 1.7	17.2, 2.6	18.3, 2.8	14.7, 2.1	4.1, 1.6	7.8, 2.7	2.0, 1.4	1.0, 2.9
4	21.2, 2.7	**20.0, 2.6**	18.2, 2.5	19.7, 2.7	17.7, 3.1	17.8, 2.1	18.4, 2.2	15.2, 2.3	3.6, 1.5	7.9, 2.2	2.1, 1.4	1.1, 2.8
5+	21.2, 3.6	18.6, 1.6	16.6, 2.9	18.6, 3.1	16.9, 1.9	17.7, 2.9	18.8, 2.7	16.0, 3.4	4.9, 2.1	7.7, 1.9	1.9, 1.0	0.5, 2.1

* based on all 249 dwellings
** based on 80 dwellings with single heating patterns
*** based on 111 dwellings with double heating patterns

The eighth heating practice metric was the time to reach peak temperature was calculated for dwellings with single and double heating patterns. For single, first and second heating periods the peak temperature was reached at the end of the heating period in 74%, 87% and 94% of the dwellings respectively. It is likely, therefore that any relationships between the technical and social descriptors and time to reach peak temperature would be similar to those for daily heating period. However, house age did not have a statistically significant relationship with daily heating period but it does with time to reach peak temperature. This suggests that although the general trend is for the peak temperature to be reached at the end of the heating period the fact that it does not in some of the dwellings is related to the technical differences between dwellings and is therefore of interest.

The longest time to reach peak temperature was found in dwellings with single heating patterns as a result of these having the longest heating periods. Average time to reach peak temperature in dwellings with a single heating period was 14.6 hours (standard deviation 2.9 hours). In dwellings with double heating patterns the time to reach peak temperature was calculated for both heating patterns and was 4.1 hours (standard deviation 1.7 hours) and 7.9 hours (standard deviation 2.4 hours) for the first and seconding period respectively. These times relate to the length of the respective heating periods with single heating periods being the longest on average and the first heating period in dwellings with double heating periods the shortest on average. This suggests that the idealised temperature profile used in BREDEM-based models is not comparable to temperature profiles in real dwellings where temperature increases throughout heating periods until a peak at the end.

House type was found to have a statistically significant relationship with time to reach peak temperature in dwellings with single heating patterns ($p=0.036$) and the first heating period in dwellings with double heating patterns ($p=0.008$) but not the second heating period ($p=0.611$). In dwellings with a single heating pattern statistical differences were found between flats (12.8 hours) and semi-detached dwellings (15.4 hours) ($q=0.004$) and flats and detached dwellings (14.9 hours) ($q=0.011$). This suggests that in dwellings with high heat loss, as result of a large proportion of exposed wall, indoor temperature takes longer to reach the peak temperature than in dwellings which has lower heat loss. Statistically significant differences in time to reach peak temperature were also found in the employment status descriptor in the first heating period in dwellings with double heating periods (p=0.030) but not in the second (p=0.907) or in the dwellings with single heating patterns (p=0.629). This may be related to dwellings where the HRP is employed having shorter heating periods and therefore this is a reflection of the length of heating periods in dwellings with different employment status and therefore does not relate to the responsiveness of heating systems.

The ninth heating practice metric is ΔT_{peak} and was calculated for dwellings with double heating patterns. According to house type the greatest difference in ΔT_{peak} was found in detached (2.2℃) and semi-detached dwe llings (2.1℃). The relationship between house type and ΔT_{peak} was found to be statistically significant (p=0.020), with the significant differences being found between flats and detached dwellings (q=0.037) and flats and semi-detached dwellings (q=0.013). The only other statistically significant relationship found in ΔT_{peak} was for the employment status descriptor (p=0.050) where the significant difference was between employed (2.1℃) and unemployed (0.7℃) groups (q=0 .048). This is again likely to be a result of the respective lengths of heating periods found in dwellings with employed and unemployed HRPs.

The tenth and final heating practice metric is ΔT_{room} which begins to shed light on the variation of temperature throughout the dwelling. 68% of living rooms were found to be warmer than bedrooms. The clearest trend in ΔT_{room} can be observed in the age of oldest occupant descriptor (p=0.008). In dwellings where the oldest occupant is between 20 and 30 ΔT_{room} was 0℃. ΔT_{room} increases with each age range and in dwellings with occupants who were over 70 living rooms were 2.0℃ warmer than bedrooms. This suggests that younger occupants are more likely to have a consistent temperature throughout the dwellings than older occupants. Considering the employment status descriptor, a statistically significant difference in ΔT room was found between the employed group (0.4℃) and the retired group (1.9℃) (p=0.001). As average winter bedroom temper ature was found to have a statistically significant relationship with household size it was expected that household size would also be related to ΔT_{room}, however, no relationship was found ($p>0.05$).

7 Discussion: implications for domestic energy modelling

This thesis has described results from a temperature monitoring study carried out in over 300 homes in Leicester. The accuracy of predictions made by housing stock energy models is partially related to the quality of assumptions used. This chapter describes how the results presented in this thesis can inform the behavioural and temperature assumptions used by BREDEM-based energy models which are commonly used in the UK as research and policy assessment tools.

Section 7.1 discusses the implication of the variation in average temperatures according to technical and social household descriptors. Section 7.2 describes the behavioural assumptions and how the findings of this work can inform them. Section 7.3 discusses the assumptions which relate to the idealised temperature profile used in BREDEM. Finally, section 7.4 summarises the points and suggests ways in which the energy modelling community can use the findings of this work to improve future housing energy models.

7.1 Average temperatures

The heat loss calculation which underpins BREDEM-8 is based on average monthly temperatures (Anderson et al, 2002). Average monthly temperatures were not calculated for each dwelling within this work but the mean winter temperature which is the average temperature for the months December 2009 to February 2010 can give an insight into how monthly temperatures during the winter vary according to technical and social household descriptors.

Directly comparable average winter temperatures measured in 25 dwellings in Northern Ireland (i.e. December – February) were reported by Yohanis and Mondol (Yohanis & Mondol, 2010). Winter living room temperatures relating to semi-detached dwellings were the highest (20.8℃) while terraced dwellings were the lowest (18.8℃). These are higher than the average winter temperatures for semi-detached dwellings (18.7℃), end-terrace dwellings (18.2℃) and mid-terrace dwellings (17.9℃) reported here. The average temperature for the winter period monitored was not reported but the average winter temperature for the region, where the dwellings were monitored, was stated to be 6℃ which is higher than average outdoor air temperature of 2.3℃ for the December to February period discussed in this work and is consequently expected to be the result of the higher measured temperatures. Unlike this work, where no relationship was found, a significant trend can be observed in Yohanis and Modol's work between winter living room temperature and household size; dwellings occupied by only one person had winter temperatures in living rooms of 16.2℃ compared to 20.5℃ in dwellings with four or more occupants. In this work household size was only related to mean winter bedroom temperature.

Oreszczyn et al. (2006) reported an average daytime living room temperature (19.1℃) and average night-time bedroom temperature (17.1℃) based on an outdoor temperature of 5℃ in low income dwellings. These temperatures are similar to the mean winter temperatures measured in this work; the slightly lower living room temperature and the slightly higher bedroom temperature is likely to be related to the different calculations methods i.e. the mean winter temperature reported here was for all hours not daytime and night-time. As in this work Oreszczyn found that winter temperatures were influenced by both technical (house type and age) and social factors (age of occupants and household size).

Summerfield et al. (2007) reported daily living room (20.1℃) and bedroom (19.3℃) temperatures in 15 low energy buildings based on an outdoor temperature of 5℃. This work found mean winter temperature for living room (18.5℃) and bedroom (17.4℃) during a period when the average outdoor temperature was 2.3℃. The lower temperatures may be partially related to this sample having higher heat loss on average than the low energy dwellings in Summerfield's study and the lower average outdoor temperature.

A number of relationships between mean winter temperatures and the technical household descriptors were found. These were largely related to the heat loss of dwellings as related exposed wall area or the U-values of the building's construction. These are generally well understood and accounted for in models. One interesting trend, however, was observed in the house age descriptor. As expected, average temperatures were lower in older homes; because of higher heat loss. Temperature increased as construction age decreased but drops again in the newest dwellings. This might be because the newest dwellings are more air tight and have low infiltration. In these homes occupants do not require such high temperatures during heating periods as their thermal comfort is not negatively influenced by draughts. This observation concurs with thermal comfort theory (CIBSE, 1999).

According to social descriptors, mean winter temperatures are related to employment status of the household representative person (HRP) (the person who answered the interview questions) and age of the oldest occupants. Currently, social household descriptors tend not to be included in housing stock energy models. At the national level this is unlikely to impact on energy use predictions, however, if models are used to predict energy use at the city or regional scale, differences in the proportion of retired occupants in dwellings is likely to influence the accuracy of predictions. For example, the 2001 census found that 14% of household occupants were retired but this figure was only 9% in the Leicester Unitary Authority; a regional model will consider the differences in the building stock but not the different proportion of retired occupants. Consequently, a model validated against national data may be unable to predict energy use accurately at the local, city or regional scale.

7.2 Heating practices

The average temperature used in BREDEM-based models is derived using a number of assumptions about heating practices as discussed in section 2.3.3. How the heating practices defined and calculated in this work can inform the standard practices suggested by BREDEM are discussed here.

7.2.1 Heating pattern

BREDEM suggests a daily heating period of nine hours based on heating periods of two hours in the morning and seven hours in the evening (Anderson et al., 2002). Although double heating patterns, as suggested by BREDEM, were the most common in this study (51%) other heating patterns such as single (33%) and multiple (5%) were also frequently used. Significantly, the heating patterns used in 11% of dwellings were too inconsistent to categorise. This suggests that in at least 11% of dwellings the heating is turned on and off manually, or the timer is overridden, on a regular basis. In these homes the occupants are responding to their needs and routines. This behaviour could even be a conscious choice to reduce energy use by only using heating when necessary, i.e. only using heating when the dwelling is occupied and could consequently become more common as energy prices continue to increase and households need to find ways to reduce energy bills.

In the context of domestic energy models, the variation in heating pattern found here is important; dwellings with single heating patterns were found to have significantly longer heating periods than those with double heating patterns. One energy model, DECM, has started to incorporate different heating periods by basing heating patterns on employment status and varying the heating times accordingly (Cheng & Steemers, 2011). This work has found similar trends, and confirms that the variation in heating period should be considered in future developments of energy models, especially if they are used to make predictions at local, city or regional levels as discussed above.

7.2.2 Daily heating period

The average daily heating period was calculated in this work was 12.6 hours (standard deviation 3.4 hours), which is more than three hours longer than the heating period used in BREDEM. It has been noted previously that the method used to calculate daily heating period is expected to result in heating periods that are longer than those used in reality. However, unlike previous methods used to calculate daily heating period the chosen method preserves the range of heating periods and this provides an opportunity to explore the social and technical determinants of heating periods. A large range in daily heating period was found, with the shortest and longest average daily heating periods being 4 hours and 22 hours respectively. Dwellings which were built before 1945 were found to have longer heating periods than newer dwellings, dwellings built with solid walls also had longer heating periods than those with cavity walls. These findings suggest that in dwellings with greater heat loss longer heating periods are chosen. This aligns with Shipworth et al.'s (2010) finding that detached dwellings have longer heating periods than the other house types. This phenomenon is perhaps a consequence of the high heat loss from older dwellings and those with a large exposed wall area. In these dwellings indoor temperatures will fall quickly when heating is turned off and will take some time to return to a 'comfortable' indoor temperature when heating is again turned on. Consequently, occupants will chose longer heating periods so that their comfort temperature is maintained during the time that they inhabit the space; for example, they may program the heating to come on two hours before they come home from work and remain on until they go to bed. While, conversely, in a thermally efficient dwelling it may only take half an hour to reach a comfortable temperature and after the heating is turned off it may remain comfortable for some time.

Statistically significant relationships were also established for daily heating periods and the employment status of the HRP and age of the oldest occupant. Occupants that are likely to spend more time at home, those that are retired or permanently unable to work, were found to have longer heating periods. It is suggested that these insights are incorporated into future energy models.

Finally, there is a point of discussion to be had about what is meant by the term heating period. In this work the heating period is the cumulative time between when the heating system comes on and goes off. It is noted that during this time the boiler does not work at a constant rate; when the temperature setting on the room thermostat is reached the boiler will stop heating water in the heating loop until the air temperature drops; and when the return temperature of the water in the heating loop has reached a certain temperature the boiler will stop heating the water in the loop until the return temperature drops (as discussed in section 2.1.2). Previous work which has estimated the duration of heating periods has used a method based on the time periods where heat was delivered to the measured space (Shipworth et al., 2010) which may more be closely related to the length of time each day that the boiler is active while the metric calculated here may give more insight into the total length of the heating period. Further monitoring of boilers and heating systems is required to deepen understanding of this point.

7.2.3 Demand temperature

BREDEM suggests that the standard demand temperature for zone 1 (living room) is 21℃ (Anderson et al., 2002). In dwellings heated by gas fired central heating, which is predominant in UK dwellings, where there is no temperature control, i.e. no room thermostat, the demand temperature is increased to 22℃. In zone 2 (bedroom) the suggested demand temperature is 18℃. The literature says, however, that where there is no independent temperature control excess heating will result, leading to higher temperatures (ibid).

The average maximum temperature calculated in this work was 20.9℃ in living rooms which is very close to that suggested by BREDEM. Shipworth et al., (2010) used a similar method and reported that the ‘estimated thermostat setting’ was 21.1℃. Shipworth’s method, however, excluded days which were not heated and consequently cannot be compared to model assumptions which assume constant behaviour. These methods may not be directly comparable with the demand temperature used in BREDEM-based models, as the idealised temperature profile assumes that the demand temperature is maintained constantly throughout the heating period. Consequently, the average temperature when heated (heating practice metric 7) is a better representation of the demand temperature used in BREDEM models.

The average temperature when heated was 18.2℃ (standard deviation 3.2) in living rooms and 17.6℃ (standard deviation 3.4) in bedrooms for single heating patterns. The average temperature during double heating patterns were 17.5℃ (standard deviation 2.8℃) in living rooms and 17.0 ℃ (standard deviation 2.7℃) in bedrooms in the first heating period and 19.0℃ (standard deviation 3.0℃) and 17.8℃ (standard deviation 2.8℃) in the second heating periods. These temperatures are 2℃ or more lower than the 21℃ commonly used for zone 1. The measured average temperature when heated in bedrooms is closer to the 18℃ suggested. It should also be noted, however, that in certain groups of dwellings the average temperature was found to be much lower, for example, in the dwellings that were built before 1919 average temperature during single heating periods was 16.5℃ and 16.0℃ for living ro oms and bedrooms respectively. If living room temperatures are 2℃ l ower than suggested by housing stock energy models, the model will overestimate the average temperature and therefore energy use. This may be compensated for by the under estimation of daily heating period.

The variation of average temperatures and heating metrics across dwellings is a significant contribution of this work. The average maximum temperature and average temperature when heated were higher in flats than in the other house types. More thermally efficient homes were also shown to have higher average temperatures. As stated above, these variations are already considered in energy models. Consequently, the variation which is related to the social descriptors is more interesting. The age of the oldest occupant had a statistically significant relationship with average maximum temperature; higher temperatures were observed in dwellings occupied by older people. Employment status was also a significant driver of variation in indoor temperature as dwellings occupied by people who are likely to be at home during the day (those unable to work or retired) were higher. These findings will again limit the ability of energy models as currently structured to be applied at the local, city or regional scales. It is suggested, therefore, that the variation in demand temperature according to social descriptors is incorporated into future building energy models.

7.2.4 Two zone approach

BREDEM-based models assume that zone 1 (living room) is heated to a higher temperature than zone 2 (bedroom) (Anderson et al., 2002). On average living rooms were 1℃ warmer than bedrooms, however, 22% o f dwellings had bedrooms that were warmer than living rooms. This represents a significant proportion of the housing stock and may have a significant impact on the accuracy of energy models.

In dwellings with more than one bedroom zone 2 will have a larger floor area than zone 1 and therefore the assumption that zone 1 is warmer than zone 2 will lead to an underestimate in heating energy required.

The difference between average living room and bedroom temperatures (ΔT_{room}) was also significant dependent on social factors. Dwellings where the household representative person (HRP) was unable to work and those with occupants over 70 years old had living room temperatures 2℃ warme r than bedrooms. In dwellings where the oldest occupant was in their 20's the average ΔT_{room} was zero. This suggests that the proportion of a dwelling that is heated may be related to the demographic make-up of the dwelling. This finding confirms the analysis of Oreszczyn et al. (2006) who found that dwellings where the oldest occupant was above 60 had higher living room temperatures and lower bedroom temperatures, i.e. ΔT_{room} was greater in dwellings occupied by older people.

Household size may also be related to ΔT_{room} as the dwellings with most occupants had more uniform living room and bedroom temperatures. Additional insight can be gained by studying the range of mean winter temperatures measured in living rooms and bedrooms. Mean winter temperature remains relatively constant with household size in living rooms but in bedrooms the average temperature increase with larger numbers of occupants. This suggests that the size of zone 1 is partially related to household size. In dwellings with more occupants the occupants spread-out into their own bedrooms and therefore a greater proportion of the dwelling is heated to the temperatures required is occupied areas.

Further monitoring studies, which measure temperature in all rooms of the house are required to fully understand how social descriptors impact on the proportion of a dwelling which is heated.

7.2.5 Heating season

Two implications regarding the heating season have been identified by this work. BREDEM literature does not specify the length of the heating season, most stock models, however, follow the method used in The Standard Assessment Procedure (SAP) (based on BREDEM-9) which assumes that dwellings are heating systems are used during the period October to May inclusive (eight months) (DECC, 2011c).

The first implication relates to the length of the heating seasons. This work suggests that 3% of dwellings are heated throughout the whole year, i.e. an extra 4 months of heating compared to SAP assumptions. Although outdoor temperatures will be much closer to indoor temperatures during these months this will still result in more energy use than predicted using standard assumptions. Other households were found to turn on their heating in mid-November and, although it was not possible to identify the end of the heating season, it is likely that many of these dwellings will have significantly shorter heating seasons than the eight months used in SAP.

The variation in threshold temperature, which is the external temperature at which a household switches on the heating system, suggests some potential for further exploration. The threshold temperature was lower in mid-terraced properties and higher in detached dwellings, which suggests a longer heating season on average will result in dwellings with a greater proportion of exposed wall area. Threshold temperature was higher in dwellings where the oldest occupant was above 60 and compared to those where the oldest occupant was under 30 and therefore the heating season may be longer in dwellings occupied by older people. Threshold temperature was found to have a statistically significant relationship with house type with dwellings with greater exposed wall area, i.e. detached dwellings, having a higher threshold temperature than those with less exposed wall area, i.e. mid-terraces. This suggests that dwellings with higher heat loss will have a longer heating season. More research looking at the length of the heating season which includes when heating systems are turned off is required to explore this further.

The second implication relates to the consistency of heating during the heating season. Heating practice metric 5 calculated the number of under-heated days during the 90 day analysis period. The average percentage of days when heating was used for less than half of the usual heating period was 3% and 16% of dwellings had 5% or more under-heated days. Across the whole housing stock these shorter heating periods will result in lower energy use than predicted by the models using standard assumptions. The number of under-heated days was found to be related to household size and the age of the oldest occupants. In dwellings occupied by a single person there were more under-heated days, dwellings where the oldest occupant was in their 20's also had significantly more under-heated days than average. This suggests that future model developments could account for under-heated days, perhaps by varying average indoor temperatures based on occupancy characteristics.

7.3 The idealised temperature profile

The heat loss calculations used in BREDEM models use an average monthly indoor temperature which is derived from an idealised temperature profile. This section describes how this work can inform the assumptions relating to the idealised temperature profile.

7.3.1 Peak temperature during heating periods

The idealised temperature profile assumes that demand temperature is maintained consistently throughout the heating period (Anderson et al., 2002). This work, however, has shown that, in the majority of dwellings, the peak temperature continues to increase when heating is used and the peak temperature is reached at the end of the heating period.

As the second heating period was found to be longer than the first heating period this leads onto another problem with the idealised temperature profile; that the average temperature in the second heating period is almost always higher than in the first heating period.

7.3.2 Temperature difference between heating periods

BREDEM assumes that the demand temperature is the same in both heating periods (Anderson et al., 2002). This work, however, has found that the average temperature difference between the first and second heating period was 1.9℃ (standard deviation 1.4℃). This difference is greater when the second heating period is longer than the first; i.e. higher temperatures (both peak and average) are the result of longer heating periods.

The variation in temperature difference between heating periods was also observed to depend on some technical and social descriptors. In detached dwellings, the temperature difference between heating periods was higher than in the other house types. A statistically significant relationship was also found between dwellings where the HRP was employed and unemployed. Both of these relationships however, are likely to result from the length of heating periods. In dwellings where the HRP is employed the first heating period is shorter on average than in the dwellings where the HRP is unemployed, where the second heating period tends to be of similar duration. This results in lower average temperatures for the first heating period in dwellings where the HRP is employed and consequently the temperature difference between the two heating periods is greater.

In order to understand the implications of this finding it is important to discuss why temperatures during the second heating period might be higher than in the first. Four possible reasons for this are suggested

1. Dwellings have poor thermostatic control and higher evening temperatures are achieved as a result of longer heating periods.
2. Occupants manage their temperature to increase in the evening (as they are less active during this time) by using secondary heating or turning up their thermostats.
3. The second heating period may also be warmer as a result of the thermal properties of the building fabric. During the first heating period the thermal mass of the dwelling will store thermal energy. Less of this energy is lost

during the day as outdoor temperatures are higher than during the night (the time between heating periods is also likely to be less than the off period overnight), consequently, during the second heating period the building fabric may be warmer and the thermal energy delivered to the space by the heating system will result in the indoor air temperature rising more quickly.

4. It is likely that the temperature measured by the sensors is a mix of dry bulb or air temperature and mean radiant temperature (CIBSE, 1999). It is consequently possible for the air temperature to remain relatively constant, because it is controlled by a thermostat which is measuring only air temperature, but the radiant temperature to continue to increase throughout the day as more heat is stored in the walls. The temperature recorded by the sensor may, therefore, increase even when a room thermostat is working correctly. As the building fabric is heated during the day the radiant temperature from the walls increases the temperature measured by the sensor.

Using the data available (as the measurement period is too long i.e. 1 hour) it is not possible to know which of these reasons is responsible for the phenomenon which is observed. The implication of this finding, however, is that the average temperature in BREDEM-based energy models is overestimated as the demand temperature in short heating periods in the morning is lower than suggested in the idealised temperature profile. The overestimation is also not uniformly distributed across the housing stock so the error in energy use predictions will be greater in certain segments of the housing stock.

7.3.3 Inconsistent heating patterns

The idealised temperature profile assumes that all dwellings are heated in the same way each day or that the profile is an average of the different days during that period. The two previous sections have shown that there is a significant variation in heating practices between dwellings. Furthermore, this work has shown that 16% of dwellings had either multiple (more than two heating periods) or inconsistent heating patterns i.e. the on and off times of the heating were changed regularly. This suggests another weakness and potentially more problematic shortcoming of the idealised temperature. The different heating patterns used are also related to occupancy; double heating patterns were the most common (51%) but in dwellings with someone over 70, retired or unemployed single heating patterns are most common.

It has also been discussed that most dwellings have a number of under-heated days where shorter heating periods than average are used. Dwellings occupied by a single person or people in their 20's were found to have a higher number of under-heated days. This is further evidence that indoor temperatures and heating practices are related to social household descriptors and that there is potential to develop housing stock energy models which consider not only the technical variation between dwellings but also the impact on heating practices of the occupants.

It is acknowledged that in any model assumptions and simplifications are necessary, however, it is suggested that the idealised temperature profile could be improved if the empirical findings of this work are taken into account.

7.4 Summary

The assumptions used in BREDEM-based models which relate to the heating practices used by household occupants and the use of the idealised temperature profile have been discussed.

A number of heating practices have been highlighted that are related to social and technical household descriptors, which BREDEM standard assumptions overlook. These discrepancies will reduce the accuracy of housing model predictions which are validated at the national level but are then used to make predictions at the local, city or regional scales. It is noted that differences between the average heating practices found in this work and those used in BREDEM will not necessarily result in the average monthly indoor temperature being incorrect as it is possible to arrive at the same average monthly indoor temperature using a number of different heating assumptions. For example, homes with a longer heating period that will increase the average monthly temperature may also have a lower demand temperature which will tend to decrease the average monthly temperature. This has resulted in housing stock energy models being successfully validated against national energy use data even though they use a number of incorrect assumptions. This is problematic when the model is used to assess a particular intervention or for energy use in a sub-section of the housing stock such as one house type or a region which may not have a representative sample.

This work has shown a large variation in average indoor temperatures and heating practices. Housing stock energy models account for this variation when it is related to technical differences i.e. proportion of exposed wall area and U-values but in general do not generally consider the impact of occupants. Average values for the ten heating practices have been provided for a number of social and technical household descriptors. Using these figures a modelling approach which uses additional social descriptors could be developed. The first step might be to change the heating practice inputs according to one additional social characteristic, for example, age of the oldest occupant. In dwellings where the age of the oldest occupant is over 60 longer heating periods and higher indoor temperatures will be used; while the opposite was found in dwellings with younger occupants. The results of this model could then be validated and extra complexity added.

Sourcing the extra information required to build a model which incorporates the findings of this work is an additional challenge for housing stock energy modellers. The English Housing Survey (EHS) provides both the age range and the employment status of the HRP but this is a nationally representative sample and would still not be applicable at the local or regional scale. As technical and social household descriptors are available for over 16,000 dwellings this data source, however, could be used to develop a nationally representative model which incorporates additional social characteristics which may result in more accurate predictions.

It is noted that some of the heating metrics are influenced by each other, for example, dwellings which have a high number of under-heated days are likely to have lower average temperatures when heated and longer heating periods were found to result in higher average and peak temperatures in heating periods. It is consequently a significant challenge to incorporate the complexity of the findings described in this thesis and is likely to require an iterative process to ensure that the additive nature of the new information does not skew results wildly. As the input variables are changed (heating period and demand temperature) the model will calculate average monthly temperatures which can be checked against the empirical temperatures reported here to validate the process.

Where it is not possible to source data additional social data on the single house scale, Census data could also be incorporated into housing stock models to enable the development of city scale predictions. Aggregate data on the age of occupants in dwellings is available at Lower Super Output Area level (approximately 500 homes) and consequently models could increase or decrease the heating practice inputs based on the aggregate data available.

Including the variation in indoor temperatures and heating practices that is related to household characteristics would reduce the error in housing stock energy models which is related to the use of standard heating practice assumptions and allow models to make more accurate predictions at the local city and regional scales.

Further work which identifies how heating practices change over time, and whether they are affected by external weather conditions, would be valuable for the development of enhanced behavioural assumptions within dynamic energy models.

8 Conclusions

This thesis has described the collection of indoor temperatures monitored in the living room and bedroom at hourly intervals in over 300 dwellings in Leicester during the period July 2009 to February 2010. These temperatures have been used to identify how mean winter temperature (December – February) in UK dwellings varies according to social and technical household descriptors. Ten heating practice metrics which start to describe how households interact with their heating systems and the indoor temperatures which heating systems deliver have been developed. These metrics give valuable insight into the range of heating practices that are used across the housing stock.

The temperature data collected was checked and where data from dwellings was unsuitable for analysis these dwellings were excluded from the analysis, the final data set used for this analysis consisted of 249 dwellings.

This final chapter is a summary of the results, describes the main conclusions and makes suggestions for future research.

8.1 Main conclusions

The main conclusions of this work can be broken down into two categories; those that relate to mean winter temperatures and those that relate to the heating practices used by household occupants to control their heating system.

8.1.1 Mean winter temperatures

Mean winter temperature (the average indoor temperature for the period between December 2009 and February 2010) was calculated for 249 dwellings to gain an initial understanding of the data, to show how average winter temperatures relate to those measured in previous studies and explore whether indoor temperatures can be predicted using survey data.

- The mean winter temperatures measured in living room and bedroom spaces are 18.5℃ (standard deviation 3.0℃) and 17 .4℃ (standard deviation 2.9℃) respectively. Mean winter temperat ures were similar to the average winter temperatures reported in previous monitoring studies. Four technical (house type, house age, wall type and central heating or not) and four social (tenure, age of oldest occupant, employment status and household size) descriptors were found to have a statistically significant relationship to the mean winter temperature in dwellings.

- It is concluded that the variation relating to technical differences between dwellings is accounted for in steady-state building energy models, but the variation that is related to the social descriptors should be accounted for in future model developments. This will ensure that models can be applied at various spatial levels which are not representative of the national housing stock.

- Multiple regression analysis was undertaken to identify the proportion of the variation in mean winter temperature that could be explained by survey data, only 24% of the variation in mean winter temperature could be explained. It is concluded that this approach could not be used to predict mean winter temperature in dwellings and it is suggested that the remaining variation is related to how households use their heating systems.

- It is noted that the average outdoor temperature during the analysis period (December 2009 – February 2010) were unusually cold and consequently some of the results reported in this thesis may be skewed. For example, mean winter temperatures are likely to be low because of high heat loss; this may also explain why it was observed that indoor temperatures took so long to reach demand temperatures and could have also resulted in longer heating periods than would have been found during a more representative winter.

8.1.2 Heating practices

Ten heating practice metrics were developed which give insight into the variation of heating system usage and the indoor temperatures which are delivered. It is acknowledged that the heating practice metrics presented here are not solely related to occupant behaviour but are also influenced by the responsiveness of heating systems and the thermal performance of the dwelling, but in each case the household is able to impact on the metric by changing how the home is heated.

Heating practice metrics related either to the timing of heating system use or the temperatures which are delivered by the heating system. The five heating practice metrics which relate to timing are:

1) The start date of heating season – which is the date in autumn after which household occupants regularly heat their homes
2) Heating pattern – is the number of times per day which heating is predominantly used
3) The start and end time of heating – which are the first and last times in the day when heat is regularly delivered by the heating system
4) The duration of the daily heating period – which is the average number of house for which heating is used per day during the winter (December – February)
5) The number of under-heated days – which is a number of days when heating is used less than half of the average number of hours heated per day

The five heating practice metrics related to temperature are:

6) Average maximum temperature – which is the average of the daily maximum temperature in living rooms (i.e. the highest temperature recorded in a living room each day)
7) Average temperature when heated – which is the average temperature measured between the most common start and end times of heating as reported in heating practice metric 3

8) The time to reach peak temperature – which is the length of time between the start of the heating period and the time at which the peak temperature is reached

9) ΔT_{peak} – which is the difference between the peak temperature recorded in the first and second heating periods in dwellings with double heating patterns

10) ΔT_{room} – which is the average temperature difference the living room and bedroom over the winter analysis period (December – February)

A large variation in each of the heating practice metrics across households was observed. Analysis of variance was used to identify if any of the variation in each of the heating practice metrics was related to social and technical household descriptors.

- The heating threshold temperature was calculated to identify the start of the heating season and was defined as the running mean of external air temperature after which heating was regularly used in a dwelling. The range of threshold temperatures found was 8℃ to 18℃ deg rees. This range indicates that some dwellings may be heated throughout the whole year, while others only during the coldest winter months. Statistical tests showed that there was a statistically significant relationship between heating threshold temperature and mean winter temperature (December – February). This suggests that the heating threshold temperature is an indicator of the sensitivity of household occupants to changes in outdoor air temperature. Households with a low threshold temperature started using their heating systems later in the year and heated their dwellings to lower indoor temperatures.

- The average duration of daily heating period was 12.6 hours. This is longer than the total heating period used in BREDEM-based models and those reported in previous work. This is partially related to the calculation technique which considers the longest regular heating period. Unlike previous techniques the method used accounts for boiler cycling and is able to identify dwellings with long and short heating periods. The longest and shortest heating periods found were 22 hours and 4 hours respectively. Daily heating period was found to have a statistically significant relationship with employment status and the age of the oldest occupant. Longer heating periods were found in dwellings where occupants are expected to be present in the dwelling during the day; i.e. those that are retired of permanently unable to work.

- The number of under-heated days was calculated to identify the proportion of the analysis period (December – February) that dwellings were heated for a short time or not at all. The average number of under-heated days was 2.9 (standard deviation 4.4) in the 90 day analysis period (i.e. 3% of days). 39% (i.e. 96 of the 249 dwellings) of the sample had no under-heated days and 17% of dwellings only had 1 under-heated day. 22% of the dwellings were under-heated for between 2 and 4 days during the winter period. 8% of dwellings have more than 10 or more under-heated days during the winter period. The highest number under-heated days recorded was 38 (42% of the analysis period). It was found that dwellings occupied by one person or by people had a larger proportion of under-heated days than dwellings with higher occupancy levels. Dwellings where the oldest occupant was in their 20's have nearly twice as many under-heated days than the dwellings with where the oldest occupant is over 30. Dwellings occupied by a single person and those by young people are therefore likely to use less energy as a result of under-heated days; this should be considered in developments of housing stock energy models.

- The predominant heating pattern in each dwelling was identified. Two heating patterns dominate the sample; single (33%) and double (51%), where heating is used once and twice per day respectively. A single heating pattern was found in 59% of the dwellings where the household representative person (HRP) (the individual whom answered the interview questions) was retired compared to 23% of the dwellings where the HRP was employed. Inconsistent heating patterns were found in 11% of dwellings which suggests that household occupants turn heating on and off when required based on when the dwellings is occupied and external temperatures on a given day.

- The most common start and end times for heating periods were identified (Table 8-1). It was found that dwellings where the HRP was employed which used a double heating period had a first heating period which started and finished earlier than the other employment status groups.

Table 8-1. The most common start and end times of heating in dwellings with single and double heating patterns.

	On	Off	On	Off
Single	7:00am/8:00am	11:00pm	-	-
Double	6:00am	9:00am	4:00pm	9:00pm

- Average temperatures when heated were calculated for dwellings where single and double heating patterns were identified. The average temperature during single heating periods was 18.2°C (standard deviation 3.2°C) in living rooms and 17.6°C (standard deviati on 3.4°C) in bedrooms. In the dwellings with double heating periods average temperature during heating periods was 17.5°C (standard deviation 2.8° C) in living rooms and 17.0°C (standard deviation 2.7°C) in bedrooms in th e first heating period and 19.0°C (standard deviation 3.0°C) and 17.8°C (s tandard deviation 2.8°C) in the second heating period in the living r oom and bedroom respectively. Higher average and peak temperatures were found in dwellings with longer heating periods. Age of the oldest occupant had a statistically significant relationship with average temperatures when heated; temperatures increased as the age of occupants increased.

- The average living room temperature was found to be 1.0°C warmer than the average bedroom temperature, however, 32% of bedrooms were found to be warmer than living rooms. ΔT_{room} had a statistically significant relationship with age of oldest occupant; in dwellings occupied by younger people it was found that living room and bedroom temperatures were more similar.

- BREDEM-based models use an idealised temperature profile as the basis of their heat loss calculations. It has been shown that this profile differs significantly from real world temperature profiles. Specifically, peak temperature is generally recorded at the end of the heating period. It was also found that 97% of the dwellings with double heating patterns have peak and average temperatures that are higher in the second heating period. Temperatures in BREDEM models are based on an idealised heating profile which assumes that indoor temperature stays constant during heating periods; this has been shown to be inaccurate as indoor temperature tends to increase throughout the duration of the heating period.

8.2 Recommendations for further research

This work aimed to explore the determinants of mean winter temperatures and to develop heating practice metrics which provide insight into the use of domestic heating systems. Through pursuing this aim a number of key findings have been made but there are areas where data collection and analysis techniques could be improved, additionally there is scope for further research in building energy modelling which could quantify the range in energy use that results from the variation in heating practices that have been found in this work. There are, consequently, two areas in which this work could be progressed which would be beneficial; in-situ building performance monitoring and building energy modelling.

8.2.1 Building performance monitoring

There were a number of limitations to this analysis which resulted from the method used for temperature monitoring in this study. For future temperature monitoring studies to ensure more accurate temperature measurements and better analysis techniques a number of refinements should be made to monitoring methods.

First is the placement of temperature sensors, in this study the household occupants were asked to place the sensors, instruction was given but it was not possible to know whether this instruction was adhered to. Ideally, sensors should be placed by trained energy researchers; however, in large scale studies the use of trained professionals can soon become prohibitively expensive. There are also concerns over privacy; household occupants may be uncomfortable with researchers having access to certain rooms. It is also noted that for participants to continue in the research they do not want sensors to be place in unsightly places on full view, there is therefore need for compromise.

The placement experiment undertaken as part of this study gained important insight into the possible variation in temperature readings in a single room. This work should be repeated to establish the impact of house type and age etc. on the distribution of air temperature in a single room. Furthermore placement experiments should be repeated in different rooms of the dwelling, i.e. upstairs and downstairs. This would be difficult in occupied dwellings, due to the number of sensors required, but may be possible as results can be established with very short monitoring periods. The completion of this work would aid in the delivery of large-scale temperature monitoring studies as findings may allow researchers to identify if there are any building characteristics which make a dwelling more likely to have a large variation in temperature in single rooms. This would consequently allow for the error in temperature measurements to be quantified.

This work was an assessment of heating practices over the whole winter period; however, one additional piece of analysis which would strengthen this work would be to assess how heating is used differently during weekday and weekends. This would ensure that any inconsistent heating patterns observed are related to actual behaviour not just varying practices during different times of the week.

A further development of this work would establish the air flow in dwellings. Thermal comfort of occupants is likely to be an important driver of heating practices and this is related to both air temperature and air flow (CIBSE, 1999).

For example, this work showed that mean winter temperature was higher in dwellings which were built more recently apart from the newest dwellings where mean winter temperatures were found to be lower than measured in the previous age range, it was speculated that this was related to the newest dwellings being more airtight which would mean that occupants would feel warmer at lower temperatures due to reduced draughts.

It was discussed that some of the calculations of heating practice metrics developed were limited as temperature was only measured each hour. For example, heating periods were calculated by identifying whether temperature increased from hour to hour, however, heating can be controlled at any time during and therefore the estimation of start and end times of heating have an associated error of plus or minus 1 hour and consequently duration of heating period has an error of plus or minus 2 hours. The temperature fluctuations resulting from boiler cycling make spot measurement of temperatures an inaccurate way of measuring temperature during heated periods. Future temperature monitoring during winter periods should therefore use sensors that report the average temperature over the logging period or sensors that can be set to log at much higher resolution. If temperature was measured every minute short term changes in air temperature relating to the presence of household occupants near to the sensor, window or door opening, or heat gains that relate to cooking could be eliminated by averaging a number of temperature readings.

A development of this research into heating practices would be the insight gained by energy monitoring. This would have two very important outcomes. First, if high resolution gas use data could be monitored (say every 5 minutes or less) this would allow for a robust validation of the methods used to calculate the heating practices related to timing. It is noted that the use of smart meters would reduce the need to make assumptions based on temperature data for the timing of heating systems and the start of the heating season, but temperature monitoring would still be important to establish the indoor temperatures in dwellings and therefore the relative heat loss. Second, if energy use data was available this work could establish how much of the variation in energy use in each dwelling is related to the heating practice metrics which were derived.

Finally, this work and other temperature monitoring studies have monitored temperature in a limited number of rooms in each dwelling. The increased use of central heating and additional temperature controls available, via thermostat radiator valves, questions the simple two zone temperature assumptions used in BREDEM-based building energy models. This work has shown that approximately 30% of bedrooms are heated to higher temperatures than living rooms but no insight could be given into the variation in temperature throughout the whole dwelling. Whole house temperature monitoring would not only inform the assumptions in BREDEM-based housing stock models but also would have application in dynamic modelling.

8.2.2 Domestic building energy models

Three possible developments of the work presented in this thesis which relate to energy modelling are outlined.

The first is an assessment of the impact of the variation in heating practices as shown in this thesis using building energy models. This could be achieved using a limited number of building archetypes based on house type and age and comparing the maximum, minimum and mean heating practices with the standard assumptions recommended in BREDEM literature. These results would show the impact of the actual variation in occupant behaviour on energy and CO_2 predictions in individual houses and would inform the development of future stock models.

The second relates to the use of the heating practice metrics in the development of future housing stock energy models. This thesis has provided ten heating practice metrics which are related to a number of technical and social household descriptors. The heating practice inputs of housing stock energy models could be varied according to additional information. For example, dwellings where the age of the oldest occupant were found to have longer heating periods and higher average temperatures during heating periods. The length of the heating period and the demand temperature could be increased in these dwellings and shortened in dwellings where the age of the oldest occupant is below 30. This is noted that this is a challenging endeavour and will increase the complexity of models due to the increased difficulty of sourcing data and the interactions between the heating practices that have been outlined. The inclusion of social characteristics, however, will ensure that models can be successfully applied at local, city and regional scales.

The third possible development relates to the use of the idealised temperature profile for the calculation of average monthly temperature which is used as the basis of the steady state heat loss calculations in BREDEM-based models. This work has shown two ways in which the idealised profile differs from the temperature profiles collected in real dwellings; [1] average temperatures recorded in the two heating periods in a single dwelling are not the same and are not only related to the thermostat setting used but also the length of the heating period; [2] temperatures increase throughout the heating period which leads to the peak temperature being recorded at the end of the longest heating period (usually in the evening). A simplified heating profile which took into account these two findings should therefore be developed. This would ensure that the indoor temperatures which are represented in building energy models more closely align with temperature profiles measured in real homes.

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