A Socio-technical evaluation of the impact of energy demand reduction measures in family homes

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Table of Contents

List of Tables

List of Figures

Abstract

Energy consumption in the home depends on appliance ownership and use, space heating systems, control set-points and hot water use. It represents a significant proportion of national demand in the UK. The factors that drive the level of consumption are a complex and interrelated mix of the numbers of people in the home, the building and system characteristics as well as the preferences for the internal environment and service choices of occupants. Reducing the energy demand in the domestic sector is critical to achieving the national 2050 carbon targets, as upward of 60% reduction in demand is assumed by many energy system scenarios and technology pathways. The uptake of reduction measures has been demonstrated to be quite ad hoc and intervention studies have demonstrated considerable variation in the results. Additionally, a limitation of many studies is that they only consider one intervention, whereas a more holistic approach to the assessment of the potential of reduction measures in specific homes may yield a better understanding of the likely impact of measures on the whole house consumption and indeed would shed light on the appropriateness of the assumptions that underpin the decisions that need to be made regarding the future energy supply system and demand strategies.

This work presents a systematic approach to modelling potential reductions for a set of seven family homes, feeding back this information to householders and then evaluating the likely reduction potential based on their responses. Carried out through a combination of monitoring and semi-structured interviews, the approach develops a methodology to model energy reduction in specific homes using monitoring data and steady-state heat balance principles to determine ventilation heat loss, improving the assumptions within the energy model regarding those variables affected by human behaviour. The findings suggest that the anticipated reductions in end use energy demand in the domestic sector are possible, but that there is no 'one size fits all' solution. A combination of retrofitting and lifestyle change is needed in most homes and smart home technology may potentially be useful in assisting the home owner to achieve reductions where they are attempting to strike a balance between energy efficiency, service and comfort.

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List of publications

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Cosar-Jorda, P. and Buswell, R.A., 2015. Estimating the air change rates in dwellings using a heat balance approach. Energy Procedia, 78, pp.573-578.

Cosar-Jorda, P., Buswell, R.A. and Mitchell, V., 2013. Estimating the potential reductions in energy demand through efficiency, control and lifestyle change in a real home. Proceedings of futurebuild 2013, University of Bath, UK.

Cosar-Jorda, P., Buswell, R.A., Webb, L.H., Leder Mackley, K., Morosanu, R. and Pink, S., 2013. Energy in the home: Everyday life and the effect on time of use. Proceedings of BS2013: 13th Conference of IBPSA 2013 International Building Performance Simulation Association, Chambery, France.

Chapter 1

Introduction

The burning of fossil fuels produces double the amount of CO_2 emissions that natural processes can absorb, resulting in a net increase of 10.65 billion tonnes of atmospheric CO_2 per year (U.S Department of Energy, 2007). Greenhouse gases contribute to global warming by enhancing radiative forcing, which is the positive difference between the incoming and outgoing energy through the earth. This effect causes the rise in the average surface temperature, which the vast majority of climate scientists agree will have major adverse effects (Protocol Kyoto, 1997). World carbon dioxide emissions at the current pace, are expected to increase by 1.9% annually between 2001 and 2025 (EIA, 2016). Most of the growth is caused by the consequences from the development of emerging economies such as China and India which are based on fossil-fuel energy use; emissions from developing countries are expected to grow above the world average at 2.7% and are predicted to surpass emissions from industrialized countries by 2018. The United Nations Framework Convention target on Climate Change under the Kyoto Protocol, was to decrease the emissions to 3.7 Gt/a by 2050, thus limiting global average temperature increase to below 2℃ (Protocol Kyoto, 1997).

The ambitious British low carbon target was formally established in the 2008 Climate Change Act with the primary objective of reducing CO_2 emissions by 80% by 2050, while procuring a national secure energy system (UK Parliament, 2008). To ensure regular progress towards the UK long-term target, the Act established a system of five-yearly carbon budgets, which is developed by the Committee on Climate Change, an independent statutory body founded under the Climate Change Act.

In order to achieve a secure energy system, the system needs to offer energy services in the quality and quantity that energy users need and want, at the time they want and at an affordable price ensuring physical, economical and geopolitical security (Staley et al., 2009). A resilient energy system is capable of delivering affordable energy services to consumers allowing disturbance and speedily recovering from shocks and changing external circumstances (The Technology Strategy Board, 2009). Therefore, the higher the energy demand, the more difficult it is to enable a secure energy system.

Energy consumption in the UK including transport, industry, public and domestic sectors, increased 2% since 1990 to 2010, remaining fairly constant in the last twenty years and being expected to stabilize in the future (Skea et al., 2011). Although the UK's final energy demand has not changed much between 1970 and 2010, the sectoral mix has changed considerably. Energy consumption in the industry sector has dropped by nearly one third, the service sector decreased by 5% and consumption from the transport and the domestic sectors have risen by 13% and 19% respectively (Department of Energy & Climate Change, 2012a). The main reason for the increase in the transport sector, was due to air and road transport growth.

Growth in the energy produced by renewable technologies will eventually reduce fossil fuel reliance, and this forms an important target in the UK agenda towards the low carbon economy, especially for future low carbon electricity generation. The low carbon Transition Plan, launched by the British government in July 2009 aims at 30% of renewables and 40% of low CO_2 sources. The introduction of renewable energy systems will generate significant challenges in order to balance supply and demand (Skea et al., 2011). Fossil fuels will play an important role in the energy mix for some time to come, acting as a back up to ensure energy security, but generating consequent emissions which work against climate change policy goals, at least before the implementation of carbon capture and storage technologies.

1.1 The domestic sector and its role towards 2050

The UK targets for energy demand reduction are challenging and will impact energy consumption in the built environment in particular. Domestic energy consumption accounts for about 40% of the UK total energy consumption and 25% of the country's emissions, and hence its contribution is significant. The challenge for domestic energy demand is to reduce emissions by 31% by 2020 based on 1990 levels (Department for Environment Food and Rural Affaires, 2007) and by 60% by 2050 (Centre for Sustainable Energy, 2008). The implementation of energy reduction measures at a national level is challenging, entailing the participation of households, numbering almost 25 million.

Reduction measures such as refurbishment, energy-efficiency, low carbon and zero carbon technologies are considered to be relatively easy to achieve in the domestic sector, as many energy-efficient and low-carbon technologies are available or in development in addition to the scope for improving the UK dwelling energy efficiency (Boardman et al., 2005).

Energy reduction in homes, however, is not just a matter for retrofit measures. It depends on a number of variables such as: appliance ownership, control settings for space heating, system efficiency, hot water and appliance use patterns, number of people living in the home, occupancy schedules and users preferences on heating settings and use of appliances and lighting (Summerfield et al., 2007; Boait et al., 2012; Gram-Hanssen, 2010; Santin, 2011; Santin et al., 2009; Guerra-Santin and Itard, 2010; Shipworth et al., 2010).

There are currently 'smart home' systems on the market such as Control4 or VeraEdge Z-Wave Home Automation which increase the control users have over their consumption (British gas, 2016; Control4, 2014; Vera Control Ltd, 2014); high efficient appliances and systems are continuously being introduced on the market while new trends change gadgets functionality and users expectations.

The application of demand reduction measures in households is challenging because: options are numerous; their impact on consumption is not obvious making capital outlay difficult to evaluate; and suitability and effectiveness is dependent on the lifestyles, routines and preferences of the occupants (Breukers et al., 2011; Darby and McKenna, 2012; Hargreaves et al., 2010; Shove and Warde, 2002). The limitations people impose on the effectiveness of reduction measures and indeed the benefits of applying them are often overlooked. A well documented consequence of the ineffective application of reduction measures is the so-called 'rebound effect', where improvements have been carried out on a building but the energy savings realised are far lower than anticipated (Hong et al., 2006).

The evaluation of the effectiveness of reduction measures tends to overlook important variables affecting energy consumption; for example, because they are based either on modelling tools with poor input variables or insights from limited intervention studies evaluations of 'popular' measures at a national scale or the actual rather an optimal order of retrofit applied by householders (Simpson et al., 2016). In addition, published work does not tend to treat the household as a system of interdependent variables that include the building fabric, systems and occupants. This leads to assumptions that have significant influence on insights from reduction measures that are shaping national predictions and technology roadmaps towards future energy consumption.

This work addresses these issues by considering the household as a whole system into which a range of reduction measure options can be applied and evaluated. The approach develops a model based analysis framework built around the availability of detailed monitoring data from households that has the potential to offer targeted reduction impact information to be delivered to individual households. The results from the analysis of a sample of UK households are used to challenge assumptions made about the expected levels of domestic energy demand reduction nationally.

1.2 Aim and objectives

The aim of this work is to evaluate the impact of demand reduction measures on the energy consumption of family homes.

The aim is met by attaining the following objectives:

1. Review the academic literature on domestic energy consumption and identify the potential energy reduction measures and their impact on energy consumption, the methods that have been used for the reduction evaluation, as well as the challenges that need to be overcome to improve previous evaluation approaches and to effectively implement measures in domestic dwellings.
2. Develop a research framework that can quantify the impact of reduction measures on specific households and evaluate the suitability of a set of measures against the lifestyles and preferences of the occupants (Chapter 3).
3. Develop a modelling approach that is capable of using household monitored data in order to characterise specific household energy consumption, including the estimation of the dwelling ventilation rate (Chapter 4).
4. Establish a whole-house reduction model and an approach to quantify the effects from applying measures individually, the balance between lifestyle and investment opportunities and the impact of all combined measures, as well as the tailored proxy target towards 2050

(Chapter 5).

5. Evaluate the potential reduction in domestic energy demand through the detailed analysis of a sample of family households in order to establish a 'maximum' reduction for each house that can be compared with the 2050 target, evaluating the balance of lifestyle and investment options and the impact of each energy reduction measure (Chapter 6).
6. Establish willingness of householders to undertake reduction measures, identifying the barriers that prevent them from applying the changes (Chapter 7).
7. Quantify the influence of householder's attitudes and preferences to reduce energy consumption, by reapplying the reduction models using the feedback data elicited from the interviews to gain a more realistic sense of the 'likely' level or reductions (Chapter 8).

Chapter 2

Literature review

Energy demand reduction in the domestic sector has an important role in the UK 5^{th} Carbon Budget. Home energy efficiency and changes to consumer behaviour are seen as a critical component in reducing the cost of meeting the 2050 energy targets (Committee on Climate Change, 2015). There are over 22 million homes in the UK, 26% of which were built before the 1930s and 16% after 1985 (Department for Communities and Local Government, 2012). Building characteristics vary due to regulatory conditions related to the time of construction (Beaumont, 2007), having improved over the years up to current zero carbon standards. Zero carbon standards are aimed to impact on new housing, although considering projections of the 2050 housing stock, an estimated 75% of the dwellings are already built (Wright, 2008). Improving the energy performance of existing buildings is one of the key challenges towards 2050, and it is recognised as a socio-technical problem. This work develops a socio-technical approach to investigate the likely demand reduction through improved efficiency and behavioural change in a sample of houses; to support this, the literature review reflects on the relevant information regarding: characteristics of UK household energy consumption; opportunities for energy reduction; and, socio-technical research approaches that have been used to investigate these issues.

2.1 The UK housing stock

The English House Condition Survey classifies the following building types: houses, which can be small terraced, medium/large terraced, semi-detached and detached; bungalow and flats, converted, low-rise purpose-built and high-rise purpose built. Semi-detached and detached houses account for 80% of the UK stock. Dwelling size varies considerably between households;

the average usable floor area per dwelling is over $90m^2$ for private households and $70m^2$ for those in social housing.

Owner occupied dwellings constitute the 64% (Office for National Statistics, 2011) and although energy efficiency has improved over the last 20 years, it is still the house tenure with the highest potential for energy efficient measures (Department for Communities and Local Government, 2016). The current UK average figure of dwelling occupancy is 2.3 people per dwelling; number which has decreased over time; half of the dwellings have at least 3 bedrooms and 37% of owner occupied dwellings are occupied by 2 people and only another 37% are occupied by more than 2 (Boardman et al., 2005). Family homes with and without dependent children are the most common household occupation, constituting almost 70% of the UK (Office for National Statistics, 2011).

2.1.1 Space heating and hot water

Historically space heating accounts for the highest proportion of the energy use in UK household energy service (Utley and Shorrock, 2008); UK space heating consumption is above the EU-15 average, constituting 62% of the domestic energy consumption in 2011 (Department of Energy & Climate Change, 2013). Since 1970 space heating consumption has risen over a tenth, increasing sharply from 1970 to 1986, largely due to the spread of installed central heating (Department of Trade and Industry, 2007). Other factors for the increasing energy use in space heating is the growth in number of households (up from 18.8 to 27.1 million an increase of 44%) and the demand for warmer houses. Nevertheless, improvements in house insulation and heating system efficiency have partially offset the effect of household growth, and the demand for warmer homes, although the resulting energy use in homes was still 17% higher since 1970 (Department of Energy & Climate Change, 2013).

Space heating is delivered through a central heating system in 90% of households, most by a gas boiler, which also provides hot water in 85% of dwellings (Department for Communities and Local Government, 2012). The implementation of central heating systems in the UK homes has led to a considerable increase in the average indoor temperature, rising from an average of 12℃ in the 1970 to 18℃ in 2011 (BRE, 2013). Space heating energy consumption has increased, notably in detached houses which have greater number of exposed walls and in old or 'hard to treat' houses with low levels of thermal insulation and air tightness (Banfill et al., 2011b). Domestic dwellings heated by central space heating systems are usually heated for longer than needed, heating also unoccupied spaces (Department of Energy & Climate Change, 2012c; Meyers et al., 2010); this is partially due to the limited use of heating controls, which together with householders' behaviours towards natural ventilation can result in inefficient space heating consumption (Kvisgaard and Collet, 1990).

The insulation of dwellings is becoming increasingly important. Minimum insulation and infiltration levels are determined by building regulations in order to minimise heat loss through the fabric and infiltration of cold air in new and retrofit buildings. Upgrading existing housing is key to achieving energy demand reductions, since many of the existing dwellings will remain in 2050 (Boardman et al., 2005). The refitting of the existing stock includes measures such as insulating cavity walls, adding insulation to solid walls, insulating ground floors and lofts and updating the building glazing to double or triple high quality glazing. The level of integration of these measures have increased considerably since 1996; by 2011, 69% of the stock had external cavity walls and 38% of all dwellings had cavity wall insulation; 30% of households had loft insulation over 200 mm thick, and 76% of dwellings were fully double glazed with an additional 12% which had better glazing than double (Department for Communities and Local Government, 2012).

The heating system and the boiler efficiency are key for minimising the space heating supply; boiler performance standards have been mandatory in the UK since 2005. Condensing boilers are around 10% more efficient than the average non-condensing boiler, and can reach overall efficiencies of over 90% (Department of Energy & Climate Change, 2012c).

Over 9 million condensing boilers have been installed since 2005; as a consequence, the percentage of dwellings with non-condensing combination boilers fell from 29% in 2006 to 19% in 2011 and the less efficient back boilers have decreased to 6% in 2011. In 2011, 38% of the UK domestic building stock had a condensing boiler installed (Department of Energy & Climate Change, 2013).

In 85% of dwellings, hot water is also provided by the main gas boiler. Hot water is the third energy driver in the home, accounting for 18% of whole house energy demand in 2009 (Boait et al., 2012). The range of hot water consumption reported by the Energy Saving Trust, who monitored 120 dwellings in 2008, varies from less than 25 L/day to over 300 L/day per household, which is mainly driven by behavioural factors (Energy Saving Trust, 2008a). Energy use for hot water production is not just dependant on the amount of hot water used, and the efficiency of the boiler, but on the temperature settings and the heat loss through the piping.

Space heating controls

Central space heating systems are managed by users via programmable time clocks, room thermostats and thermostatic radiator valves. Even though 88% of heating systems in the UK households had some kind of control by 1996, the effectiveness of these is far lower than predicted, partially because many householders do not fully understand how to use them (Heating and Hot Water Taskforce, 2010). This can lead homes to be heated above an optimum temperature range and heating homes during times of non-occupancy (Department of Energy & Climate Change, 2012c; Meyers et al., 2010). Temperature choice and on time are two key variables driven by householder preferences that impact upon space heating consumption (Shipworth et al., 2010). There are currently many smart thermostats on the market such as Hive, Tado, E-ON touch, Nest, Control4 or VeraEdge Z-Wave Home Automation Controller. Smart thermostats aim at increasing the easy and effectiveness by which users can control domestic space heating systems (British gas, 2016; Samsung, 2016; Control4, 2014; Vera Control Ltd, 2014; Honeywell International Inc., 2014; OWL, 2014; Sangani, 2014). Smart control systems enabled through ICT can provide real time feedback and the ability to automatically adjust indoor temperatures. Market penetration of these is expected to increase and become more effective to users, eventually leading to energy reduction if users' comfort and convenience needs and investment expectations can be met without counter-acting reductions. The rebound effect is the term used in energy studies to describe this phenomena, where improved efficiencies are compromised by greater use or higher temperatures. Energy demand has increased in some cases as increases in technical efficiency have led to reduced costs leading to consumers using energy consuming goods and services more. (Khazzoom, 1989). The rebound effect has impact upon technical improvements on space heating and cooling services, water heating, lighting and appliances, showing a potential increase of consumption up to 50% in the US and up to 18% in the EU (Greening et al., 2000; Galvin, 2014).

Ventilation and infiltration

Ventilation and infiltration rates impact significantly on the space heating energy required in a dwelling; the number of ACH [1] in a naturally ventilated dwelling is the result from the air flowing through the infiltration paths of the building and that from the intentional opening and closing of windows and doors. Traditionally, natural ventilation has been the common strategy for UK

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[1] ACH: Air Changes per Hour

residential buildings ventilation unlike other countries such as Sweden or Norway (Sherman and Chan, 2006). Air tightness standards are part of the UK building regulations from 2010 in order to achieve air-tighter dwellings (Department for Communities and Local Government, 2010). As buildings become more air tight, the opening of windows and doors becomes more important to achieve a balance between air quality and energy consumption. Mechanical ventilation has historically been a solution in public and commercial buildings in the UK but can be an option for domestic dwellings as these become more air tight (Hall et al., 2013; Banfill and Peacock, 2007; Banfill et al., 2011b).

Empirical values for ventilation and infiltration air change rates in domestic dwellings vary. For example, Wallace investigated a Virginia house over a year, finding a maximum figure of 0.85 Air Changes per Hour when windows were closed, and up to 1.7 ACH when windows were opened (Wallace et al., 1988); another study by Howars-Reed et al. affirms that opening a single window can increase the air change rate by a proportional amount to the width of the opening, generating increments of up to 1.3 ACH (Howard-Reed et al., 2002); and opening multiple windows reached an increment of up to 2.7 ACH. In his survey of Danish dwellings, Keiding et al., found that more than half of householders opened windows during the autumn nights and more than a fourth in winter nights, almost the whole sample ventilated the house at least once a day by opening one or more windows (Keiding et al., 2003). The effect of ventilation behaviour was further investigated by Kvisgaard and Collet, who found a large difference in ACH between a number of similar dwellings, caused by the behaviour of the occupants (Kvisgaard and Collet, 1990). An early study quantified the effect of occupant behaviour on ventilation in air conditioned houses, concluding that 87% of the air change rate was caused by the occupants behaviour (Iwashita and Akasaka, 1997).

Nevertheless, the air within buildings needs to be continuously refreshed with the outside air for the breathing air quality, reducing pollutants, and controlling moisture (Crump et al., 2005; Sundell et al., 1995; Emenius et al., 1998, 2000; Banfill et al., 2011b). Research in this area is important to ensure minimum standards for healthy environments in dwellings while maintaining space heating and air conditioning consumption as low as possible. Building regulations acknowledge this issue by implementing minimum ventilation rates. Many European countries consider ventilation rates above 0.5 ACH to be acceptable, and others standards are less restrictive, suggesting 0.3 ACH (Dimitroulopoulou, 2012). Minimum standards were not always met in UK dwellings and California houses according to previous studies (Crump et al., 2005; Offerman et al., 2007; Price and Sherman, 2006), suggesting that perhaps as buildings become more air tight, MVHR systems can be beneficial not only as a mean to reduce energy consumption but to ensure a healthy environment (Banfill et al., 2011b).

2.1.2 Electricity consumption

Electricity consumption, as part of whole house energy demand, is also a key factor to consider, especially since it has historically been the fastest growing energy resource demanded in the home; the total amount of electricity consumption by household domestic appliances between 1970 and 2014 grew by 2% per year over this period (Department of Energy & Climate Change, 2015b). One of the key factors for this increase is the constant growth in appliance ownership, particularly ICE, 'Information, Communication and Entertainment' devices. The use of ICE devices includes increased home computer ownership from none in 1981 to 67% in 2005 (Market Transformation Programme, 2006). In the 1970s the average number of appliances found, was 17 gadgets per household (Meyers et al., 2010; Energy Saving Trust, 2006) whereas in 2012 the mean number of appliances reported by a national study was 41, being as high as 85 (Zimmermann et al., 2012). Home technologies can make household activities more convenient and less time-consuming (Gatersleben and Velk, 1998). However, the historical increase of comfort and convenience in the home implies an increasing environmental problem due to the associated energy penalty (Shove, 2003).

Since 1970, the use of energy in the home has considerably changed, responding to dynamic user needs; overall, there has been a continued fall in the proportion of energy use for water heating and cooking while the proportion of lighting and appliances has grown.

The most conclusive variables that have impact on electricity consumption are: household type, appliances ownership, socio-economic context, usage pattern, weather and season (Yohanis, 2012; Schipper et al., 1982; Mullaly, 1998; Palmborg, 1986; Brandon and Lewis, 1999; Baxter et al., 1986; Mansouri et al., 1996); but there are other factors that affect domestic electricity consumption, such as, food purchase, shopping trends and cooking routines. For example buying pre-packed food and buying in bulk, which have resulted in the ownership of bigger and more cold appliances despite the decreasing average number of occupants per household (Zimmermann et al., 2012; Sanne, 2002).

2.2 Review of reduction measures

The UK CO_2 targets require a reduction in emissions of 80% by 2050 (UK Parliament, 2008). This challenge is of special interest for the domestic sector. It offers many opportunities that could lead to a reduction in energy consumption, which will in turn impact CO_2 emissions. Energy consumption in the residential sector has been the focus of these interventions for some time and insights such as those from the Building Research Establishment are being used to shape socio-political initiatives towards a low carbon housing stock (Department of Energy & Climate Change, 2012b). Government policies have been launched to facilitate the implementation of more efficient heating systems, improved billing, consumption feedback and greener energy production; some of these are in place and some have already ceased, for example the Green Deal. Other programmes such as ECO, the Renewable Heat Incentive and Energy Performance Certificates are designed not only to ease the uptake of energy efficiency measures, but also, to encourage lifestyle change, intended to motivate people to retrofit and attempting to reduce the 'rebound effect' associated with retrofit and ICT.

In order to develop a strategy for achieving CO_2 targets, a number of scenarios have been developed by a range of academic, industrial, commercial and governmental organisations, trying to assess how the UK can achieve its emissions targets. Scenarios make assumptions about the future energy mix and the demand characteristics for each sector depending on economic projections, legislation regimes, technology developments etc. Some scenarios, such as those developed by the Department of Energy and Climate Change, provide pathways towards the accomplishment of targets, whereas other scenarios driven by potential societal, economical and political trends, are used to visualise how likely trends may impact on the energy landscape.

The Lifestyle Scenario, The Carbon Plan and the UK White Paper 2007 (Department of Trade and Industry, 2007), describe some of the likely key energy production and consumption characteristics which, eventually, will enable the reduction of domestic carbon emissions. Home energy reduction opportunities are summarised in this section, referencing energy research that has studied the impact from energy measures in households and the assumptions within scenarios that analyse possible domestic futures towards the 60% domestic reduction by 2050.

Future scenarios predict a significant decrease in CO_2 emissions for energy production due to the implementation of renewable sources (Roscoe and Ault, 2010) and the increase of localised domestic energy production (Department of Energy & Climate Change, 2011b). Existing future scenarios that describe possible landscapes towards 2050 CO_2 reductions examine not just public policy measures, fuel prices, economic growth and technical improvements but also an important cultural shift (UK Energy Research Centre, 2009); over a span of less than 35 years, substantial technological and cultural changes are expected to shift everyday life in the home. Housing low carbon scenarios describe more smartly controlled houses, more efficient appliances and heating systems, stronger regulations for product design and labelling and higher energy prices (Boardman et al., 2005).

What is less clear is the level of reductions that households can achieve by applying energy measures to their current consumption, and which daily life practices can be modified to lead to the highest reductions. In addition, the impact of user willingness to apply change is not certain, as well as the impact on energy reduction that householders needs and aspirations have in the reduction potential (Haines and Mitchell, 2014).

Although there have been significant assumptions made about the expected levels of energy reduction from dwellings, more research is needed to underpin the likely uptake of reduction measures, and indeed the assessment of the reduction potential tailored to real consumption in dwellings. Such work is needed if the assumptions contained within scenarios and future pathways are to be tested and validated.

2.2.1 Heating and electric provision

The changes to electricity supply moving towards 2030 is especially challenging for the electricity grid, which includes the development of a flexible, smart and responsive electricity system, powered by a diverse and secure range of low-carbon sources of electricity. Electricity is currently the most carbon intensive domestic fuel, producing in average 0.5246 \$Kg CO_2 \$ per KWh (Carbon Trust, 2011). Around a fifth of the UK existing electricity capacity is supplied by coal and another fifth by nuclear power stations (Department for Business, Energy and Industrial Strategy, 2016). Future electrification of heating and transport and market penetration of decentralised energy resources is supposed to increase the network demand for electricity; and also the complexity of managing the grid, making a secure and reliable electric supply even more challenging (Quiggin and Buswell, 2016; Wilson et al., 2013).

In order to increase the efficiency of the future grid, international governments and specially the UK government are interested in developing a responsive grid where demand follows production, through the introduction of time-of-use tariffs and Demand Side Management. The roll out of smart meters by 2020 will provide users with real time information on consumption and cost (Williams, 2014). For these to be implemented, smart meters need to be displayed in the home, allowing the individual control of appliances and communication with the grid. A major challenge in the implementation of such a demand responsive grid is the role played by the users and the impact of their behaviour on the opportunity to balance consumption; users need to shift consumption in order to avoid peak demand periods either by active participation or by automating controllable loads on the grid such as washing machines, refrigerators or chargers (Department of Energy & Climate Change, 2009; Electricity Network Strategy Group, 2010).

In order to achieve a low carbon secure energy system, renewable energy production is crucial. The 2009 Renewable Energy Directive set a target for the UK to achieve 15 % of its energy consumption from renewable sources by 2020 which will impact on carbon emissions, energy price and availability; also, decreasing the reliance on imported fuels and the uncertainty with gas and electricity price, and therefore contributing to supply security (Department of Energy & Climate Change, 2009; Boardman et al., 2005; Wolfe, 2008). One of the main challenges is that introducing renewable energy systems creates greater intermittence in the supply, which is ambitious for the energy sector, where demand must be met whilst balancing generation (Molderink et al., 2010). Further home heating de-carbonisation may come from the content change of the gas in the existing gas grid to biomethane and hydrogen, and the deployment of heat networks connected to low carbon sources (Department of Energy & Climate Change, 2012c).

Additionally, the implementation of low carbon and zero carbon technologies are not always suitable to implement in individual households and communities (Caird et al., 2008); for example heat pumps, which are challenging to implement in existing buildings, as installing such units requires major internal disruptions (Boardman et al., 2005). Other technologies such as solar water heating, micro combined heat and power (CHP) and Photovoltaics are conceivable in most buildings, but have still some barriers to be cost effective and generally deployed. Solar water heating, for example, is able to provide heat for a minimum installed surface, being far more cost effective when there is a large demand and not the best option for an average family home. Technologies like biomass or CHP can either supply heat to individual dwellings or communities, even though the main potential for biomass is within rural dwellings and suburban areas. The main inconvenience of micro-CHP is its high price, being most likely to be implemented in dense urban areas communities where network provision is most cost-effective

(Boardman, 2007; Boardman et al., 2005).

A summary of low and zero carbon (LZC) technologies is shown in Table 2.1 highlighting which of the LZC technologies are low carbon and which are zero carbon and if they can supply heat, electricity or both heat and electricity.

Table 2.1: Low and Zero Carbon technologies (Boardman, 2007).

	Heating only	**Heating and electricity**	**Electricity Only**
Low-Carbon	Heat pumps (ground and air)	Combined heat and power (CHP)	-
Zero-Carbon	Solar thermal: biomass boiler or stove	CHP from energy using waste or biomass	Solar PV, micro-wind or micro-hydro

2.2.2 Central heating systems

Since the majority of energy in the UK average home is supplied for space heating purposes, there is particular interest in optimising the thermal performance of the housing stock. The transformation of the housing stock to the target level would eventually reduce CO_2 emissions by 34.5% which means a huge opportunity and challenge for the refurbishment of existing dwellings and the standard of new buildings (Department of Environment Transport and the Regions, 2000). New dwellings need to achieve zero carbon standards by 2020 at the latest, so heat loss standards as well as ventilation heat loss through cold air infiltration are becoming very tight. Refurbishment of the existing stock to the standard of current Building Regulations for new dwellings is considered since most of the existing houses will still be standing in 2050 (UK Energy Research Centre, 2009). Also, new high efficient heating systems will be installed widely, phasing out non condensing boilers and increasing new boiler efficiency levels to 95% (Boardman et al., 2005).

Heating system controls allow the user to set the space heating on and off times and the heat intensity (either by selecting a temperature or an intensity set point). Heating controls were declared by The UK Department of Energy and Climate Change in 2009 to enable high energy reductions, although the evidence on which this was based on was claimed to be insufficient (Shipworth et al., 2010). The Market Transformation Programme reported in 2005 that householders ignoring or abusing existing heating controls wasted 14 TWh of energy a year. Findings from Shipworth et al. suggest that households that use central heating system controls, such as a room thermostat, electronic programmer and thermostatic radiator valves, have no lower demand temperatures or durations than households that do not use controls (Shipworth et al., 2010). The inclusion of heat emitter controls was claimed to lead to 17% energy reduction by Energy Saving Trust in 2008, but evaluations of energy efficiency schemes have provided increasing evidence of a performance gap between predicted and monitored energy use after applying such energy efficiency measures. Key challenges facing the efficient implementation of domestic space heating controls rely on a combination of householder knowledge on how to use them efficiently and, most importantly, to correctly use the heat emitter controls, which varies with boiler type, size, heat emitter characteristics, temperature choice and temperature outside (Peeters et al., 2008).

The development of advanced control technologies could play a key role in engaging and enabling users and improving system operation, given the importance of system efficiency under different heat load requirements. Examples of existing technologies which improve system operations are Time Proportional Integral, modulating controls and weather/load compensation systems, which increase the operational efficiency of condensing boilers. Smart home technologies designed to engage users can supply the following services to potentially improve efficiency:

- real time feedback;
- self-adapting controls such as NEST which automatically adjust the indoor temperature based on previous behaviour;
- advanced energy management systems: digital systems such as Tado, Hive or OWL to control temperature and time settings and provide feedback consumption; and,
- other controls that can automatically switch off the heating if a window is opened or if a room is not occupied.

More advanced HEMS [2] are entering the market; these can monitor consumption at a radiator level as well as supplying increased home automation and control. Such systems can potentially

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[2] HEMS: Home Energy Management Systems

help users to reduce energy consumption (Allcott, 2011; Ayres et al., 2012; Nolan et al., 2008; Bittle et al., 1979; Brandon and Lewis, 1999; Darby, 2010). The connected appliance market is also growing with consumers now able to purchase appliances that can be switched on and off remotely as well as providing feedback on energy consumption, and in the near future, operational efficiency and diagnostics to support maintenance (Tompros et al., 2009).

2.2.3 The retrofit challenge

Retrofit is the application of new materials, products and technologies into an existing building with the aim of reducing the energy demand to occupy the building (The Technology Strategy Board, 2014). Retrofit is theoretically differentiated from renovation or refurbishment, which is intended to repair or aesthetically enhance a building (The Technology Strategy Board, 2013). Nevertheless, dwelling energy efficiency is often improved as a side-effect of home improvement, but it is thought to be rarely the main incentive for change (Cameron, 2011).

Retrofit opportunities range from cost-effective measures, such as insulation of cavity walls, replacement of old windows with double, triple and other glazing systems and placement of thicker insulation in lofts, to less cost-effective solutions such as insulating solid ground floors, updating already refitted windows or applying surface wall insulation (The Technology Strategy Board, 2013). Cold air infiltration can eventually be minimised by blocking chimneys, sealing skirting boards and service pipes penetration, draught-proofing windows and doors, building junctions, and the ground floor, cutting down air pathways to achieve as low infiltration rates as in new buildings (Boardman et al., 2005; Hall et al., 2013). New materials such as taped vario vapour membrane and higher householder awareness on the importance of sealing the house are key for major savings (The Technology Strategy Board, 2013; Hall et al., 2013; Banfill et al., 2011a; Cosar-Jorda et al., 2013).

A list of 23 possible reduction measures was outlined as part of the Swedish BETSI program, 18 of those are technical, requiring only the replacement of part of the building or its systems (Mata et al., 2010). The 18 technical measures are separated in six groups based on the building element which is involved; these are shown in Table 2.2: measures that affect the ground floor (1-5), the insulation of the façade (6-8), the loft insulation (9-14), the replacement of windows (15), the use of a ventilation system (16-17) and the change from electrical power to hydro pumps (18). The combination of these measures with other behavioural measures were modelled to result in a potential of 68% energy reduction in the Swedish building sector.

Table 2.2: Technical opportunities for energy reduction, (Boardman, 2007).

Individual measure	**Group measure**	**Description**
1	1	Change of U-value of floors above crawlspaces
2	1	Change of U-value of flat floor on ground
3	1	Change of U-value of floor above unheated basements
4	1	Change of U-value of basement wall above ground
5	1	Change of U-value of basement wall below ground
6	2	Change of U-value of facades (curtain wall, outer layer)
7	2	Change of U-value of facades (outer layer covering brick facade)
8	2	Change of U-value of facades (intermediate layer, new brick facade)
9	3	Change of U-value of attic joists, from the inner side
10	3	Change of U-value of attic joists, replacement of the roof
11	3	Change of U-value of attic joists, from top side (400mm)
12	3	Change of U-value of attic joists, from top side (300mm)
13	3	Change of U-value of knee walls
14	3	Change of U-value of slope roofs
15	4	Replacement of windows
16	5	Upgrade of ventilation systems with heat recovery, for S- houses
17	5	Upgrade of ventilation systems with heat recovery, for F-apartments
18	6	Change of electrical power to hydro pumps

Previous research on the potential from retrofit measures applies modelling methodologies and empirical data from retrofits to quantify the potential reduction. Bottom up methodologies such as that from the Swedish BETSI suggest a potential energy reduction of 68% in the Swedish building stock. Similar results were found by the CALEBRE project (The Midlands Energy Consortium, 2013) from the E-On House (E-on, 2016), which built with the 1930s standards, was retrofitted to analyse the potential from a set of intervention measures packages, which results in an energy reduction between 60% and 71% (Banfill et al., 2011a). The project Retrofit for the future, analysed the energy reduction after retrofitting 37 properties in the UK and the sample properties achieved a reduction in CO_2 emissions that ranges between 50% and 80% compared with 1990 average levels (The Technology Strategy Board, 2013).

The benefits from retrofitting interventions are measured by considering the reduction in CO_2 emissions, the energy reduction achieved, the fuel cost savings and the cost-effectiveness of the intervention.

The output achievable reduction depends on many technical and human-oriented variables that can not be overlooked when evaluating its potential, particularly considering the cost and disruption that retrofit undertakes. The reduction potential of a retrofit intervention varies with the original status of the house, the set of retrofit measures performed, the energy use for space heating in the dwelling before and after the implementation of the reduction measure and with the sequences and timing followed to implement retrofit measures (Simpson et al., 2016). Householders' interest in retrofitting is often driven by reasons other than reducing energy consumption, which suggests that the main reason for householders to invest in house refurbishment is to raise the house value in the market and to meet psychological goals and lifestyle aspirations (Cameron, 2011). Further to that, there are many reasons for householders not to undertake reductions, for example, Karvonen suggested that the uncertainty of the final cost involved, the cost of the retrofit itself, the risk of problems that might appear after the implementation of measures, the aesthetic changes, the impact on the value of the house and the disruption from the installation process, are strong reasons to stop householders from implementing reductions (Karvonen, 2013).

Achieving the expected reduction through the implementation of reduction measures in the UK housing stock is a great challenge because of the need to raise the interest of householders, reach cost-effective results and be responsive to the needs of both the occupants and the building characteristics. All of these require considerations in order to design successful schemes in order to reduce domestic CO_2 emissions (The Technology Strategy Board, 2013).

2.2.4 Appliances and lighting technology

The EU has adopted a number of measures to improve European energy efficiency since 1995, when European regulation introduced energy efficiency minimum standards. Measures impacting domestic appliances and boilers include mandatory energy efficiency certificates for building sale and rental; minimum energy efficiency standards and labelling for boilers, household appliances and lighting 'EcoDesign' (Directive, 2012); periodical national energy efficiency EU action plans; the roll-out of electric and gas smart meters by 2020; and the periodic energy audit from large companies to enable easy and free access to real-time and historical energy data (Boardman, 2007; European Commission, 2016).

The Department for the Environment, Food and Rural Affairs, 'DEFRA' is the UK agency responsible for the ecodesign of energy related products regulations, and is also responsible for the implementation of the 1W initiative endorsed by the International Energy Agency. The Energy Saving Trust estimates that home waste from leaving appliances on when not in use surpasses £900 million per year, especially appliances for food preparation such as microwaves whose standby load does not affect their main function (Department of Trade and Industry, 2007; Loveday et al., 2008). Legislation has determined that incandescent bulbs will be replaced by CFLs [3] and LEDs [4] after 2020 (Skea et al., 2011). Bulbs that can be fully controlled from an iPad or mobile phone are already on the market, for example the 'Hue personal wireless lighting' (Philips, 2016). Nevertheless, the implementation of energy efficient light bulbs has not been completely successful so far due to their different performance in the home (e.g. slow to reach full brightness). Also, lighting studies suggest that lower consumption levels often cause users to become indifferent about leaving lights on (Boardman, 2007; Rodriguez and Boks, 2005). Energy labels have a limited impact on householders' energy choice, as most users are not aware of their appliance efficiency (Yohanis, 2012). An effective energy label should not just establish minimum standards and avoid inefficient appliances production but promote, at the point of sale, efficient usage, together with information on recommended sizes (Yohanis, 2012). The effectiveness of implementing new domestic technologies has so far been insufficient, as bigger appliance size, less householders per dwelling, appliance ownership increase, increasing use of ICE devices and other behavioural aspects have reduced the size of the reductions being achieved (Coleman et al., 2012).

2.2.5 Lifestyle, occupancy and user choice

Environmentally friendly lifestyles are expected to become a social norm (Skea et al., 2011). In future lifestyle projections, feedback and information will increase people's awareness of energy to enable and encourage lower consumption levels. Information measures take several forms ranging from informative bills to instantaneous feedback through smart meters. Potential reductions from lifestyle changes have been studied to be between 5 to 20% (Boardman and Darby, 2000).

The Energy Saving Trust estimates that an average household could save 10% of their heating energy use by turning their heating controls down by one degree Celsius (Energy Saving Trust, 2011b). Future scenarios such as Energy 2050 (Skea et al., 2011) propose an important cultural shift on indoor temperature settings where overheating will be considered a social issue, unacceptable in the future, suggesting 17℃ the maximum indoor temperature. Nevertheless, these expectations are in some cases against current research, which suggests that 17℃ is under

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[3] Compact Fluorescent light

[4] LED: Light Emitting Diode

the user thermal comfort temperature range, especially for vulnerable people such as the elderly; The WHO [5] guidance for air temperature in the home suggests a range between 18-24℃, changing from the previous suggestion of 15-25℃, established in the 1950s, and supported by evidence on thermal comfort research (Ezratty et al., 2009). Further research on energy reduction measures suggests that reducing the heating system set back temperature overnight has a great impact on energy consumption: for each degree Celsius increase, there was an increase of $520kWh$ in annual energy consumption, suggesting that a bimodal heating pattern would be more efficient than continuous heating (Moon and Han, 2011).

Future pathways towards CO_2 reduced emissions assume lifestyle changes and anticipate that householders will respond to energy price signals and social sustainable values (Skea et al., 2011). However, several studies argue that energy is not visible to users and that they are not always rational in their actions (Warde, 2005), which makes it difficult to predict the real reduction from interventions. The design of energy demand reduction interventions, therefore, needs to consider lifestyle values which impact on energy consumption including comfort, convenience preference and social norms (Poortinga et al., 2003; Santin, 2011; Cosar-Jorda et al., 2013).

Householders are key to the successful implementation of energy demand reduction measures since they are the only agents able to adopt, ignore, reject, adapt, or subvert low carbon actions in the home (Boardman, 2007). In order to reduce energy consumption, several trials have looked at how people react to energy information and feedback and how personal and community responsibility can be socially accentuated. Better information and feedback is being developed through more detailed billing, the implementation of smart meters, website information and home monitors. However, the effectiveness of such interventions has so far been varied (Allcott, 2011; Grønhøj and Thøgersen, 2011; Ayres et al., 2012; Nolan et al., 2008; Bittle et al., 1979; Brandon and Lewis, 1999; Darby, 2010; Weiss et al., 2010; Wood and Newborough, 2003; Poortinga et al., 2003; Santin, 2011).

Personal responsibility could also be achieved by valuing clean energy and punishing carbon emissions, for example by increasing the energy price or by allowing a carbon emissions limit per person/household as described by (Fawcett and Fawcett, 2007; Roberts and Thumim, 2006). The effect of such measures has been trialled and effectiveness is believed to be based on framing people targets and, giving a context to understand their actions (Boardman, 2007). Other ideas to enhance people's awareness about their emissions responsibilities are through

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[5] WHO: World Health Organisation

community-wide activities such as those studied by transition networks and carbon reduction groups (Transition Network, 2013).

A household's lifestyle and beliefs impact on their everyday life, individual choices and consequently on their domestic energy use (Tang and Bhamra, 2009; Saldanha and Beausoleil-Morrison, 2012). Social trends affect and constrain households' lifestyle and result in desires, beliefs, work patterns and leisure preferences. Important social trends which impact on home energy consumption are: the number of people living in the home, space and utilities sharing, size and number of appliances, working schedules and leisure activities. Occupancy, for example is one of the key energy consumption variables for domestic dwellings and depends on working status, activities preference and other daily constraints (Richardson et al., 2008).

Also, hot water energy usage is highly dependent on householders' values such as hygiene, showering and bathing practices, and other beliefs related to cleaning and washing (Critchley and Phipps, 2007; Zadeh et al., 2014). Further future social trends will no doubt emerge from the implementation of new practices such as the integration of electric vehicles and intermittent energy sources. How householders adapt their lifestyles in response to these changes will impact upon subsequent energy demand in perhaps unpredictable ways (Reeves et al., 2010).

2.2.6 Ventilation

Heat loss through ventilation and infiltration have a heat loss penalty that can be as high as that from fabric conduction in a typical unimproved UK dwelling (Banfill et al., 2011b). The dwelling air change rate can be reduced not just by increasing the air tightness of the building but by motivating appropriate opening and closing of windows, or alternatively by installing a controlled ventilation system. Natural ventilation in domestic buildings is influenced by many factors which interact in complex ways, for example the control of moisture during the heating season, or the removal of odour and cooling in the summer (Dick, 1950). Window opening behaviour has an impact both on the indoor air quality and especially on energy consumption (Fabi et al., 2012; Kvisgaard and Collet, 1990; Wallace et al., 2002).

Previous studies looking at the potential reduction from ventilation suggested up to 68% energy savings. For example (Martinaitis et al., 2015), in a case study in Lithuania, modelled the energy required for space heating and cooling after applying minimum air change rates based on the assumption that mechanical ventilation was installed together with an optimum use of shading.

Another study in China (Hong et al., 2006), modelled the annual heating energy savings from stopping morning natural ventilation, reporting on potential reductions around 4% of total heating energy use in the sample building.

Other studies focused instead in looking at the potential improvements from infiltration measures. For example (Ben and Steemers, 2014), studied the Brunswick Centre in London as a case study, and reported potential reductions from draft proofing interventions of around 6%; Hall studied the space heating energy requirement in a UK solid wall house case study before and after retrofitting, applying a set of retrofit packages and measuring the air infiltration at each stage, concluding that the building air-tightness is crucial for the reducion of domestic energy consumption (Hall et al., 2013; Banfill et al., 2011b).

Although previous research acknowledges how important it is to achieve balanced ventilation rates that ensure healthy environments while limiting energy consumption in domestic dwellings, modelling tools such as BREDEM are used for the evaluation of reduction measures (Shorrock et al., 2005). The limitation of these tools is their reliance on limited assumptions of ventilation air change rates, which need to be improved in order to ensure more realistic results on the ventilation reduction potential from domestic dwellings.

2.3 Measuring demand reduction

Research to date has addressed the assessment of the impact of both technological and behavioural measures through household interventions and quantitative modelling approaches. Previous studies have estimated the impact of implementing new technologies, behaviours and a mix of both in the home by comparing pre and post energy interventions, using monitored data to estimate reductions or modelling the impact of measures (Lopes et al., 2016).

The impact of behaviour change through interventions has been evaluated by applying a number of strategies: level of commitment, goal setting, information and prototypes are categorised as antecedent strategies, whereas feedback (either instantaneous, in a daily, weekly or monthly basis, comparative or individual), and rewards are classified as consequence strategies (Geller, 2002; Abrahamse et al., 2005). There are also macro level measures that can lead to energy conservation behaviours, such as economic incentives or disincentives i.e. taxes, or surcharges and regulation measures such as building certification and labelling, which effects on energy consumption are investigated (Barbu et al., 2013).

2.3.1 Interventions

The impact of behavioural reduction measures has been traditionally evaluated vie interventions. In Europe, feedback interventions have been most effective, achieving up to 20% energy reduction (Darby, 2006). Feedback interventions can be classified as follows: direct, indirect, inadvertent, and energy audits (Darby, 2006). Results from applying feedback interventions within European studies are varied. For example, savings from direct feedback interventions vary between 0 and 20%; indirect feedback studies have also claimed reductions up to 20%. Goal settings interventions were claimed for low reductions when standing alone, of up to 5%, whereas in combination with feedback they achieved up to 15% (Becker, 1978). Further reductions have been achieved through group and community based projects which claim up to 20% carbon emissions reduction (Fisher and Irvine, 2010).

These techniques have been criticised due to the lack of results transferability and durability of the effects over the medium to long term. Savings are therefore embedded in the context of the interventions, their temporary effects and the difference between samples for similar interventions (Ürge-Vorsatz et al., 2009).

2.3.2 Modelling

Data mining techniques have been traditionally used to understand the impact of technical improvements to the dwellings, especially in the public sector. In the domestic area, modelling techniques have been used regardless of the lack of performance to represent behavioural variables that impact upon energy consumption. Given the evidence of the importance that behavioural variables have to determine energy consumption, there have been trials to model the effect of those for energy conservation. For example, work by Yu et al. suggests a novel data analysis methodology through clustering techniques for identifying the effects of occupant behaviour on building energy consumption, and estimates the reduction potential from behavioural parameters by comparing similar buildings. This model is limited by daily end-use data, which cannot identify specific behaviours (Yu et al., 2011).

Quantification of the impact of behaviour change on energy consumption has been assessed by the use of engineering modelling tools. In 2014 Ben and Steemers simulated the energy use from Brunswick Centre in London after applying a scenario based model, suggesting that behaviour change was responsible for up to 82% energy reduction when analysing the impact of retrofit options under three different behaviour scenarios (Ben and Steemers, 2014). A French study on the impact of behavioural actions in office buildings simulated a number of extreme occupant behaviours to link the energy demand from each simulated action, concluding that there is a strong correlation between human activity and energy consumption (Parys et al., 2011). Further research on the impact of behaviour change was performed by Hong et al; the energy consumption from the reference dwelling was modelled considering the dwelling to be uninsulated in order to calculate the energy consumption linked to fabric heat loss, and that from applying three behaviour changes: no morning natural ventilation, temperature setback and a combination of both behaviours (Hong et al., 2006). This study, contrary to the last two modelling analysis, found little savings from changing behaviour (only 18% reduction), whereas it associates up to 60% savings to retrofit measures. Other study found similar results for behaviour change, showing 21% reduction (Martinaitis et al., 2015). Although previous results are not especially optimistic, they might overlook the potential from behaviour change as simulation tools used for the analysis lack realistic behavioural inputs, relying on limited profiles for a reduced number of typical activities that are evaluated via scenarios, combining one or more of the following effects: the control of sun-shading devices, occupancy schedules, set-point temperatures, heated area, lighting and ventilation practices. Realistic building occupant behaviour patterns are determined by a more complex set of variables and the modelling tools to evaluate the effects of those still need to be developed (Yu et al., 2011; Lopes et al., 2016). This line of research has been focused on specific energy services mostly related with thermal comfort, such as heating, ventilation and lighting, with little input from the potential of end use appliances.

Retrofitting and technical developments have been assessed via modelling tools and empirical studies. Models have been used to estimate energy savings, CO_2 emissions and cost efficiency of the different reduction measures. For example, the BREDEM model was employed to assess insulation and heating measures savings and cost of the UK housing stock (Shorrock et al., 2005) used, whereas Johnston explores the technological feasibility of achieving CO_2 emission reductions in excess of 60% within the UK housing stock with the UKDCM2 model (Johnston et al., 2005). Perhaps what is uncertain is if those technical solutions would be accepted by householders and how that lack of acceptability or interest can affect the reduction potential from technical solutions (Haines and Mitchell, 2014).

Most modelling studies suggesting energy savings from the uptake of new technologies in the home are calculated through top down models that assess policy regulation required to meet the

5th carbon budget (Committee on Climate Change, 2015). Some studies looking at domestic electricity consumption disaggregate energy reductions for end use appliances such as: cooking, laundry, cold appliances, lighting or computer equipment. This outline is followed by predictions of electricity consumption in the home, which projects an energy figure for each product group (Energy Saving Trust, 2011a). Little research has been done to quantify the reduction potential from behavioural changes in the home, due to a lack of data, effective models and mono-discipline research that focus on technical issues.

2.3.3 Socio-technical research

There is a broad consensus that energy usage in the home is the result from a number of technical and behavioural variables. Given the characteristics of domestic consumption, research demonstrates the need to apply cross-disciplinary approaches [6], in order to develop more holistic understanding of the impact of energy reduction measures (Hazas et al., 2011; Kane et al., 2015). There is a strong suggestion within the building community that research, both quantitative and qualitative, is best thought of as complementary and should therefore be mixed in research (Amaratunga et al., 2002).

Research addressing the behavioural and technical aspects of the building environment has so far been tackled either by large multidisciplinary, interdisciplinary and transdisciplinary projects or by studies which apply triangulation methods, a combination of qualitative and quantitative approaches. An example of transdisciplinary approaches to domestic carbon reduction in the UK is the CaRB, project which involved 22 academics from 5 different disciplines. It claimed that demand reduction research cannot be addressed effectively by a single discipline and that transdisciplinary teams with long-term funding can make a substantial impact, requiring as a vital component, a nationwide monitoring programme to assess progress and to ground models (Lomas, 2010).

Current research offers a range of energy projects taking a cross-disciplinary approach (Hazas et al., 2011; Sovacool et al., 2015; Wilson et al., 2013). There are a range of EPSRC funded projects, many within the TEDDI 'Transforming Energy Demand through Digital Innovation', which take a cross-disciplinary lens to studying digital innovation and its impact on energy demand in the home, for instance, REFIT, IDEAL, DEFACTO, Smarter Households, Building

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[6] cross-disciplinary approaches involve transdisciplinary, multidisciplinary and interdisciplinary methods (Mallaband, 2013)

Expertise and the LEEDR, project within which this thesis has been developed. The performance of these cross-disciplinary projects is still in development as the complexity to perform research engaging different disciplines needs to be addressed to maximise the project output (Lomas, 2010).

The use of mixed-methods in building research has started to be used within domestic energy reduction analysis. Recently, a modelling study (Lopes et al., 2016), developed an energy consumption profile to determine energy reduction from each energy service (for example lighting, food refrigeration or cooking). This model includes several assumptions on the ownership of devices such as cold appliances, the use of computer and audio-visual equipment as well as concerning the frequency of use of appliances such as the dishwasher, washing machine and tumble dryer. Further, the study reports on the extreme case scenarios of applying efficient behaviours and inefficient ones. It does not report on the impact of each behavioural driven activity and often mix technical with behavioural measures (for example, the temperature choice of the washing machine and the energy efficiency of the device). The model is based on time of use surveys, combining methods from engineering and social science to assess the behavioural potential. The results are limited by the lack of validation of the behavioural profiles and the use of poor modelling tools for the assessment of behavioural variables; the output efficient and inefficient profiles are hypothetical and lack householders' input and validation. Socio-technical research has developed further behavioural dimensions in recent multidisciplinary research, even though most have focussed on qualitative insights, not upon quantifying the impact of measures in energy consumption (Hong et al., 2015; Kashif et al., 2013).

2.4 Summary

The UK targets for domestic energy demand reduction are challenging and are intended to significantly impact energy consumption within the built environment. Domestic energy consumption accounts for about 30% of the UK total (Department of Energy & Climate Change, 2011a). Energy reduction in the home, however, is not just a matter of implementing retrofit measures, which has been the focus of most recent studies in the modelling area; it depends on a high number of variables both behavioural and technical (Summerfield et al., 2007; Boait et al., 2012; Gram-Hanssen, 2010; Santin, 2011; Santin et al., 2009; Guerra-Santin and Itard, 2010; Shipworth et al., 2010).

Feedback studies investigate the impact of information to householders upon achieving energy reduction opportunities in dwellings and reported up to 20% potential savings. Feedback studies often evaluate the impact of behaviour change implicitly with the impact of a new technology; the difficulty is to desegregate the effects from these change drivers so that the influence of both can be determined quantitively.

Energy-efficiency improvements and the reductions achieved are ultimately influenced by real-world constraints and limitations such as the rebound effect. Therefore in order to analyse these factors, integrative modelling approaches of complex issues such as energy behaviours are important tools to provide information that supports problem solving, but these need still to be developed to offer on one hand transferability and on the other hand, tailored road maps towards effective energy reduction (Lomas, 2010).

One of the key areas of development in current energy reduction modelling studies is the evaluation of ventilation routines in dwellings, as it heavily impacts on energy consumption and air quality but has so far been poorly modelled (Fabi et al., 2012), assuming ventilation routines in current dwellings and those arising from applying behavioural change (Hong et al., 2006; Martinaitis et al., 2015; Ben and Steemers, 2014). Lack of monitoring data has so far been an issue to develop tailored household profiles in simulation tools. Nevertheless, with the appearance of smaller, cheaper and more reliable monitoring equipment that enables electrical energy demand to be recorded at short time intervals, current models' profiles can be improved to fit behavioural and lifestyle differences between households (Lomas, 2010).

Previous studies agree that domestic energy research needs to be approached from a socio-technical perspective in order to investigate both the behavioural and the technical characteristics interplaying in energy demand. There is still much to understand about the potential for reducing consumption in real homes, which require either investment, or a behavioural change resulting in a reduction in service, comfort or convenience. Recent work has already tried to develop modelling tools that better represent the behaviour of the occupants in the home, even though results are limited by a lack of monitoring data to support findings and, the use of occupants' profiles grounded on survey data rather than measurement. Using monitoring data to understand the behavioural impact on energy consumption can improve current models effectiveness to quantify the potential of reduction measures, and can be used to explore the users impact on achieving energy reduction.

This chapter attains the Objective 1 set in Chapter 1 by identifying in the literature the main historical domestic energy consumption trends and by listing the suggested domestic energy reduction measures as well as their expected potential towards decarbonising the domestic sector. A review of methods identifies the need for socio-technical evaluations that use monitoring data to assess the reduction potential from reduction measures, as well as the need to consider user choice as part of the challenge towards achieving energy reductions, specially to assess the impact of user behaviour on ventilation.

Chapter 3

Research framework and data collection

This work addresses the quantification of the impact of reduction measures on energy demand in the home together with a qualitative assessment of the extent to which householders are prepared to undertake the reduction measures. This is achieved by utilising monitoring data and simple steady-state numerical modelling techniques to evaluate the impact of individual reduction measures but also combinations of measures. The socio-technical methodology developed is graphically presented in Figure 3.1, which summarises the methodological process and stages the sequence followed to graphically represent how the insights from the interviews feedback the model results.

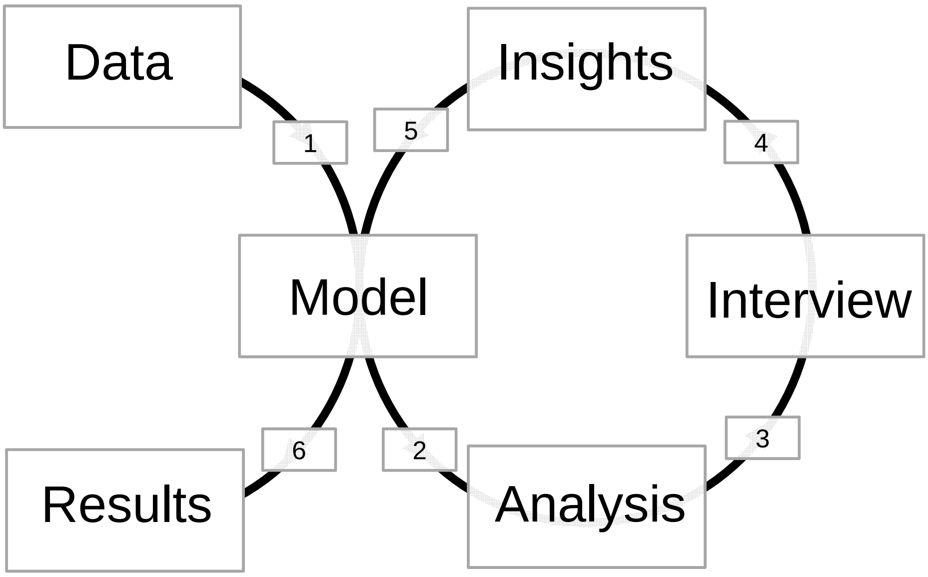

Figure 3.1: Diagram depicting the overarching approach to the research.

In order to investigate the impact of energy demand reduction measures in real family homes and the influence of family lifestyles and preferences on the likely success of these, monitoring data from a sample of 7 homes is used in combination with survey data on building, demographics and system characteristics. Monitoring data evenly distributed throughout a 12 month period from the sample of homes was used and was translated into a set of visual aids that supported semi-structured interviews. These were analysed to establish the measures that were acceptable to householders and to quantify the impact of those in energy consumption. These results were then used as prompts to reflect on the implications of the identified barriers to change and the acceptable changes.

The following methodological issues are addressed in this chapter:

- size and main characteristics of the sample of households;
- ethical considerations;
- characteristics of the monitoring data; and,
- main aspects of the qualitative data collection;

Further issues are presented in the following chapters:

- the selection of the modelling technique, Chapter 4;
- the selection of the reduction measures to model in the analysis, Chapter 5;
- modelling techniques used to estimate the impact of the reduction measures, Chapter 5;
- the assessment of the likely uptake and implementation of reduction measures by different families, Chapter 7;
- how to communicate the modelling results to the householder, Chapter 7; and,
- how to translate the results from the householder impact assessment into the assumptions within the model, Chapter 7.

3.1 Research within the LEEDR project

This mixed method research took place within the context of a large multidisciplinary academic research project LEEDR: Low Effort Energy Demand Reduction, EPSRC grant number EP/I000267/1. The research presented in this thesis began one year and a half after the start of the project. At that moment the LEEDR sample was defined and technical information was already collected as well as monitoring data and further details from self-reported surveys. As part of the PhD research, the monitoring equipment was maintained and decommissioned. Also, missing technical details were collected and householders were contacted via phone calls to be invited to the interviews, which were finally performed with the participants that agreed to take part. The data analysis and the results from the model developed over the course of the PhD were graphed and presented to the householders via the LEEDR feedback books. Table 3.1 summarises the LEEDR research activities and the year they were performed, listing those that have an interaction with this research, but which were predefined and the activities performed as part of the PhD research.

Before the start of this research the LEEDR sample was selected. As part of the selection process an initial inquiry was done via telephone interviews to explain the project to the participants and a technical visit took place to ensure the viability of the home for the project. General information about household characteristics, systems, appliances and billing information was collected via a self-reported on-line survey, which also covered demographic information. Over the course of the LEEDR project technical visits took place to capture the layout of the dwellings, dimensions, appliances ownership, system characteristics and other relevant data as well as changes in the ownership of appliances and systems. The installation of the monitoring equipment started previous to the beginning of the PhD, although its maintenance required regular visits to the household as part of the performance of this research as well as the ongoing technical visits.

Householders were inquired to take part of the interviews just before the project was coming to the end, after the decommissioning of the monitoring equipment. The researcher was familiar to the participants previous to the interviews due to the regular visits performed for the maintenance of the monitoring equipment and the collection and update of technical details.

Table 3.1: LEEDR Activities interaction with PhD research

Benchmark	Activity	Date
Previous	Initial enquiry	2011
	Initial visit	2011
	On-line survey	2011
	Technical survey	2011
	Monitoring installation	2011-2012
During the PhD (July 2012-October 2016)	Monitoring maintainance	2012-2014
	Technical details completion	2012-2014
	Monitoring decommissioned	2014
	Phone call to inquiry interviews participation	2014
	Interviews	2014
	Feedback books edition	2014

3.2 Justification of the approach

Modelling techniques have been used to quantify the energy impact from reduction measures for a number of reasons. Modelling tools are valuable for their applicability and their capability for coverage, being a fast and economical method, which provide statistical results that can apply to large samples, and therefore of special relevance to policy makers. Monitoring data can be input into physical based models by assuming either steady-state or dynamic characteristics. Nevertheless, current models are not designed to input detailed data such as electricity use from end use appliances, gas consumption from space heating and hot water or ventilation air change rates, and instead calculate energy requirements based on pre-set parameters. The use of monitored data in the domestic energy arena is claimed to be beneficial to develop more effective solutions towards energy reduction, but current energy tools are not designed to input monitoring data, because customization of the models is highly time consuming. This work presents an application of steady-state heat balance principles to develop a model that calculates energy consumption and ventilation rates based on monitoring data. The model enables the quantification of the tailored impact of a set of reduction measures. The approach is explained in detail in Chapter 4 and Chapter 5.

The approach is combined with qualitative analysis to assess the viability of energy reductions within the context of real family homes. Initially, the results from the model were limited to the assumptions embedded within the established parameters of the reduction model. These were validated by householders in order to understand whether, given their lifestyle choices it was feasible that these changes might take place within their homes and therefore validate the suitability of the assumptions used to generate the energy reduction potential. Householders were approached via face to face semi-structured interviews as described in Chapter 7.

Figure 3.2 graphically presents the research framework and the literature review linked to each part of the approach.

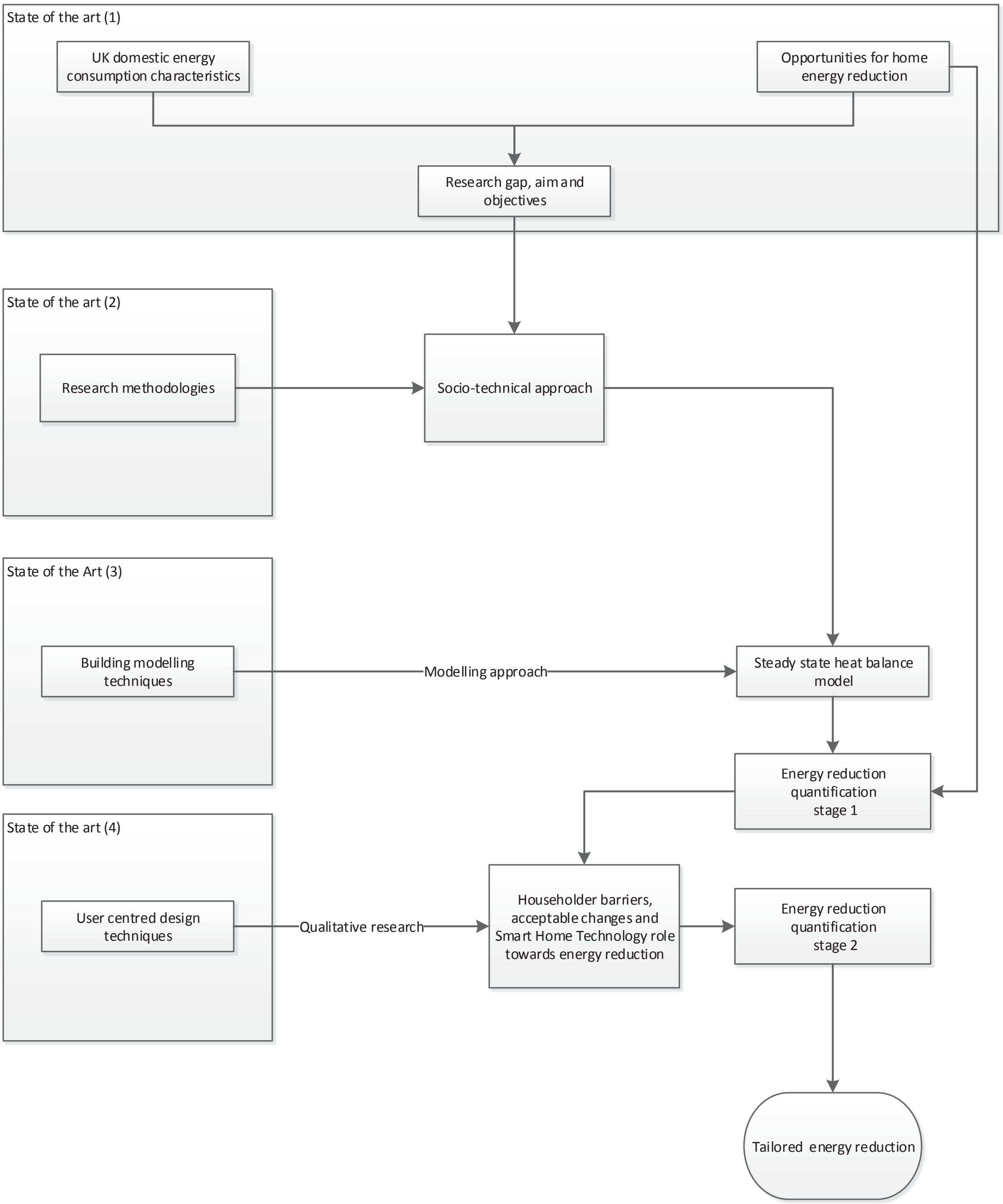

Figure 3.2: Methodology overview.

3.3 Sample selection

In 2014, there were an estimated 23.4 million dwellings in England, including both occupied and vacant homes (Department for Communities and Local Government, 2015). The UK housing stock has a variety of household types and tenure. Within the variety of household type there are married/cohabiting couples with and without dependent children, lone parent families, multi-person households (such as flat sharers or lone parents with no dependent children), and one person occupied dwellings. Household tenure is typically classified into three groups: home owners, social and private renters. The majority of owner occupied dwellings are houses (92%), and a quarter of those are detached.

The East Midlands is one of the nine English regions, which consists of Derbyshire, Leicestershire, Lincolnshire, Northamptonshire, Nottinghamshire and Rutland. Loughborough a town of near 60,000 residents is in Leicestershire. The LEEDR sample is located within a 4 miles radius of Loughborough.

The 20 LEEDR homes vary in construction but are typical of their respective years of construction, from 1900 to 2002, and of those found throughout the UK. All houses are detached or semi-detached and characteristics are varied regarding age of construction, main wall type, house size, appliance ownership and heating system characteristics.

All homes are occupied by families with dependent children that range in number and age, from 3 to 6 persons, including parents with children to families with relatives living together. The LEEDR sample represents more than a third of the household stock in terms of household type and tenure considering that owner occupied dwellings represent 64% of the UK population, and that cohabiting couples with dependent children account for 37% of the owner occupied dwellings. Of the 20 LEEDR homes, one left the project due to a house move, there were 11 with satisfactory levels of monitoring, 7 of which agreed to participate in the study. The foremost characteristics of the sample of households that took part in the interviews, are summarised in Table 3.2.

Table 3.2: Sample dwelling and family characteristics.

House	Construction year	House type	Wall insulation	Glazing	Rooms (all)	Showers number	Hot water	Appliances	Adults	21-14 years	13-8 years	7-0 years	Weekdays occupied	Away weekends
H05	1940	SD	Insulated cavity	Double	9	1	Combi	34	2	1			1day	Regularly
H09	1960	D	Insulated cavity	Double	12	2	Combi	36	2		2		4 days	Rarely
H10	1980	D	Insulated cavity	Double	10	2	Combi	39	2			2	5 days	Rarely
H30	1950	D	Solid Wall	Single	9	1	Combi	33	1		1		5 days	Rarely
H37	1970	D	Insulated cavity	Double	11	2	Combi	37	2		2		5 days	Rarely
H39	1950	D	Solid Wall	Double	9	1	Combi	42	2	1	1		1 day	Rarely
H46	1990	SD	Insulated cavity	Double	11	1	Combi	49	3		1	3	5 days	Rarely

3.3.1 Household data

General information about participants was collected via an on-line self reported survey, during household visits and phone calls. The self reported on-line survey was performed at the beginning of the project. The survey inquires the main characteristics of the building, heating system, appliance ownership, energy billing and basic demographic information, such as number and age, salary, range and educational levels of occupants. The questions surveyed can be seen in Appendix D; this survey, together with technical photos of home gadgets and floor plans, constitutes the general technical data for each house. The data was input in the model to determine household characteristics impacting on the energy balance, and was used to inform the modelling, in terms of:

- building element dimensions and characteristics;
- dimensions;
- occupancy patterns investigated, and,
- appliance ownership.

3.3.2 Building characteristics

Five homes are detached houses (D) and two, H05 and H46, are semi-detached (SD); houses were built between 1940 and 1990 and their insulation levels range from solid wall in H30 and H39, to insulated cavity walls with and without loft insulation. The glazing characteristics also varied house to house, from a mix of basic double glazed windows with timber frame from the 1950s and a percentage of single glazing, i.e. H39; to a mix of PVC framed double windows and a proportion of triple glazing, i.e. H37; The ground floor in all households but H05 is a solid concrete slab; H05 ground floor is suspended timber. House size varies from just above 100 m^2 in H30 and H39 to 170m^2 in H10, as shown in Figure 3.3, the total number of rooms (including kitchen, bathroom, hall etc) varied between 9 and 12.

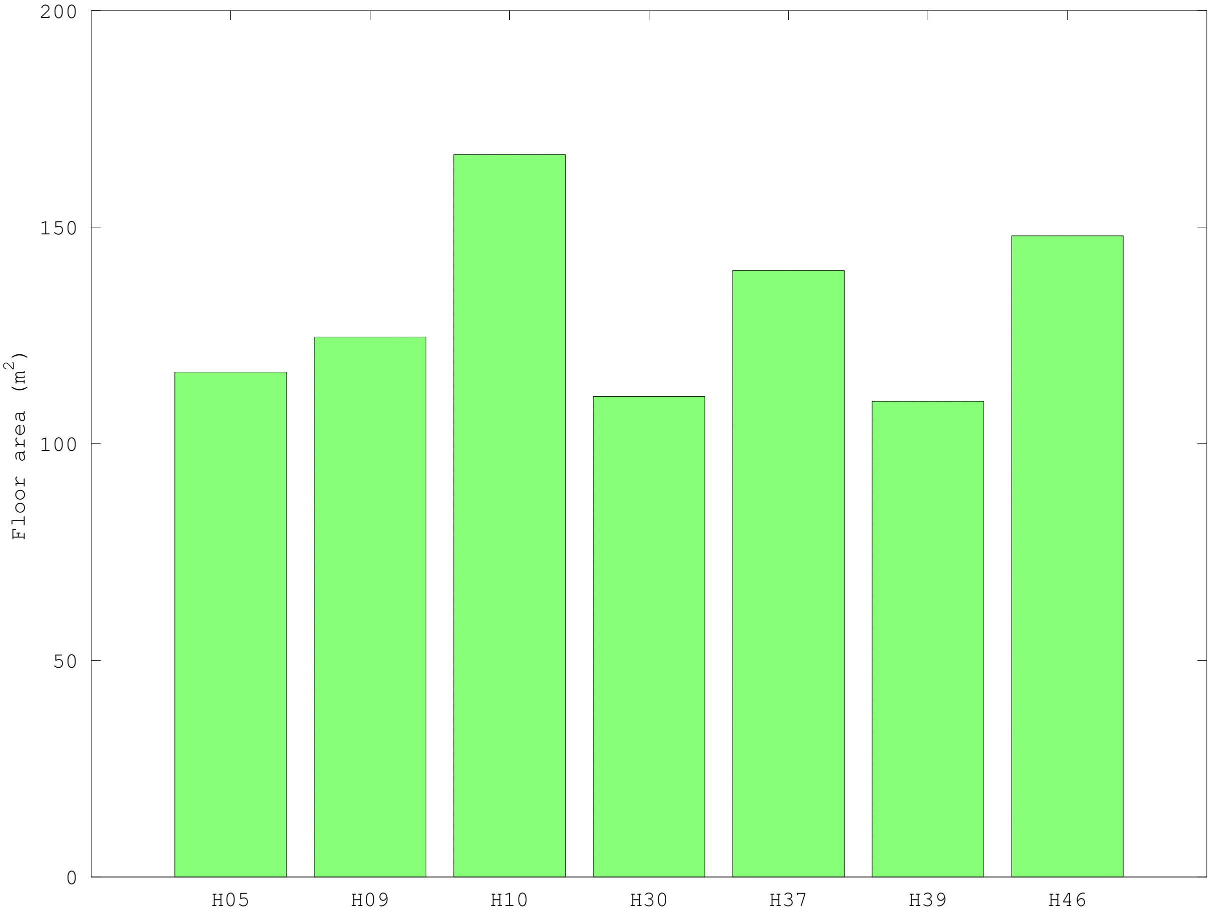

Figure 3.3: A comparison of floor areas of the houses in the sample.

3.3.3 Heating system and appliances ownership

Hot water and central space heating is either supplied by tank or a combination boiler with a range of efficiencies between 79 % and 91% as listed in Table 3.3; Figures are based on the SEDBUK rating, 'Seasonal Efficiency of Domestic Boilers in the UK' which is an indicator of boiler efficiencies developed by the UK government in conjunction with boiler manufacturers (Home Heating Guide, 2014). Showers are provided with hot water from the main boiler and/or from electric showers. The number of showers varies from one to two and there are electric showers in H09, H37 and H39. The ownership of appliances varies from 34 devices in H05 to 49 in H46.

Table 3.3: Household boiler efficiency (ϵ).

House	**H05**	**H09**	**H10**	**H30**	**H37**	**H39**	**H46**
Efficiency (ϵ)	87 %	79%	90%	90%	90%	78%	91%

3.3.4 Demographics

The sample includes a single parental family home with one child; a multi-generation family home with four children, parents and grandmother; four houses with four family members and one house with three. The most common family size was four people, two parents and two children. The age of the adults ranged from one young couple in their thirties to one mature couple in their late fifties. The rest of the sample were within their late forties and early fifties. All the families are high and middle income families with a variety of background levels from basic to post-graduate education. Two male householders, H10MA [1] and H37MA were experts in data analysis and research.

3.3.5 Occupancy

Households had partial occupancy during the week, at least one day a week, such as H05MA who works from home on Fridays, but most of them are occupied by at least one person the whole week, either partially or during working hours; this is the case for H10, H30, H37, and H46.

Households were occupied on weekdays during working hours, at least partially and weekend occupancy varied. H05, for example, is occupied on Fridays, when H05MA worked from home; H09 is also occupied on Fridays, and H39 is occupied by H39MA on Thursdays. H10, H30 and H46 are fully occupied during the week; H10FA and H30FA worked at home, whereas H46 is occupied by H46GFA; H37 is normally occupied from noon, as H37FA [2] works part time.

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[1] MA: Male Adult; code used to name anonymous individuals.

[2] FA: Female Adult

3.4 Ethics

Participants were informed about the characteristics of the study and the data required and consent forms were acquired before the start of data collection. Householders were given information about each part of the study, and then signed consent forms were collected prior to the study commenced.

Visits to participants' homes were prearranged either by e-mail or phone call. Participants were ensured confidentiality and protection of their personal data and their homes' identities, including their specific location and contents. Participant identification numbers were assigned to numerical data and qualitative notes to ensure anonymity. These were kept in an access restricted file and all of the contact information and recorded data were kept at a secure location.

The ethical information sheets designed for the participation within the LEEDR project and that for the participation in the interview are attached in Appendix E, together with the consent forms signed by all participants.

3.5 Quantitative data

The monitoring data was collected over a 12 month period (2013). Data was collected via three monitoring systems: hot water monitoring comprising an in-line turbine meter measuring hot water volume and water temperatures entering and leaving the boiler at one second intervals.Gas consumption was measured by capturing images of the meter dial every second and converting the dial rotation into an angular displacement over time, from which the equivalent volumetric flow rate of gas was inferred (Buswell, 2013).

The proprietary wireless (Zigbee) system of sensors was used to monitor whole house electricity consumption, appliance consumption, air temperature, movement and window position (opened or closed). Figure 3.4 shows the sensors installed, where Figure 3.4a, 3.4b, 3.4c,3.4d, 3.4e depict the: Passive InfraRed sensor, 'PIR', that monitors air temperature and detects movement; Current Transducer, 'CTs', which monitor power consumption by inferring current flow; magnetic sensors used to monitor the opening and closing of windows and doors; the 'SMART PLUGs' that monitor appliance electricity consumption; and, the hub to which the devices connect to be routed to servers via the internet.

(a) PIR sensor (b) CT meter

(c) Door sensor (d) SMART PLUG (e) Hub

Figure 3.4: Images of the wireless monitoring devices.

Sensors monitoring internal air temperature

Air temperature is monitored by sensors embedded in the PIR devices, which are generally located in a high corner of the room, placed where presence can be easily tracked but there is no direct sunlight. Figure 3.5 shows a sample house map with the location of window/door opening sensors (DOR) and PIR sensors. DOR sensors detect windows position and measure air temperature every two minutes.

The number of PIR and DOR sensors varies from house to house as shown in Table 3.4, where H10 is the household with less sensors installed and H30 the house with more sensors.

Table 3.4: Number of sensors per household

Household	H05	H09	H10	H30	H37	H39	H46
Number of DOR	9	11	7	11	12	5	11
Number of PIR	9	11	7	16	10	9	11

The uncertainty value of the temperature recordings is taken from previous work within the LEEDR project (Buswell, 2013), which used the same devices to calculate the uncertainty of the air temperature in a given room. The variation was estimated at ± 0.9℃.

Room	DOR-D	DOR-W	PIR
Hall	400		801
kitchen	401		
kitchen		404	800
kitchen		405	
Lounge		402	802
Lounge		403	803
Bed 2		406	806
Bath		407	807
Bath		408	
Bedroom 1		409	805
Bedroom 1 side w		414	
Bedroom window		410	
Hall upstairs		411	804

Figure 3.5: PIR and DOR sensors sample location

Electricity

A number of sub-circuits were monitored in each house using the CT devices. This varied from house to house, from 4 up to 13 circuits, including small power circuits, showers, solar PVs and lighting. The number of appliances monitored also varied between homes to a maximum of 28; key appliances such as the washing machine or the main fridge freezer are monitored in all houses. Typical end use appliances monitored by SMART PLUGs are the washing machine, tumble dryer, dishwasher, fridge-freezer, computer equipment, TV, microwave or phone battery charger.

Windows and doors state

Window state sensors were installed in each house and indicate whether the door/window is either opened or closed; opened/closed events are recorded, which is then converted to a minute wise time series to map onto the other data. The number of installed sensors per house varies in location and number, from 5 sensors in H05 and H39, to 12 sensors in H37; sensors were installed in the most frequently used openings and at least one sensor monitored each of the front and back door.

External conditions

Weather data collected by the 'Met Office Integrated Data Archive System (MIDAS)' weather station was combined with on site temperature data and input into the model. The data used within the analysis includes, air temperature (℃), and wind speed (m/s).

Data from the Sutton Bonington site, located 4 miles away from Loughborough, was used in the analysis. The average outdoor air temperature over a 24 hour period was compared with the average figure resulting from all the on site temperature measurements taken by the DOR sensors in the outside of the dwellings over the same 24 hours period. MIDAS data was 0.7 - 1.6℃ cooler than the site measurements over the year of study. As can be seen in Figure 3.6, the difference between the MIDAS sensor and the DOR sensors is specially high during the summer months, being as high as 4℃, whereas in the winter samples give closer estimates, in some cases very near to 0℃; the summer difference is most likely to be caused by localised urban warming of all homes that are in built up areas, whereas the weather station is in a more exposed rural location.

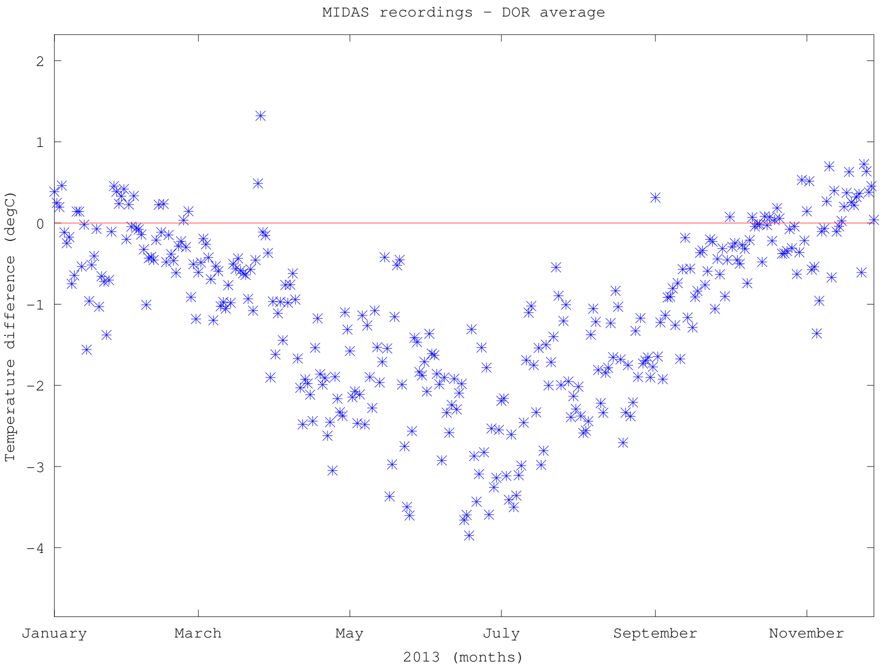

Figure 3.6: Mean daily outdoor air temperature for 2013.

Sampling intervals

The measured data was sampled at a variety of resolutions, ranging from 1 second to 2 minutes as summarised in Table 3.5. Gas and hot water data were sampled every second, whereas electric appliance consumption, circuit consumption, and window position were sampled every minute; air temperature was recorded every two minutes.

Table 3.5: Monitoring data sampling intervals.

Measurement	**Sample intervals**
Gas	1 second
Hot water	1 second
Electricity	1 minute
Windows position	1 minute
Air temperature	2 minutes

The data was then processed to a common time step of 1 minute. Minutely data was used for specific calculations within the model and aggregated to hourly or daily values for the application of the heat balance. The analysis of electrical end use appliances and gas for hot water use was carried out based on one minute resolution data in order to identify important features such as temperature difference for the water volume heated, and standby energy consumption for electric appliances. The heat input from occupants was modelled using hourly occupancy profiles and the calculation of daily energy consumption from gas and electricity was performed by aggregating the data to daily values. The calculation of fabric heat loss and ventilation was carried out over a 24 hour period. Details are provided in Chapter 4.

Measurement calibration

The calibration of the measurement devices was performed to check and verify the accuracy of the monitoring devices. The calibration of the CT devices was carried out by monitoring the power consumption readings at varying loads (120, 1270 and 2520 W) and generating an average over 30 minutes of 1 minutely samples.

In order to validate the devices' accuracy, the deviation error factor was calculated, which describes the scale of discrepancy between metered and monitored power/energy per unit, calculating it as a percentage. The deviation error was higher for low power loads (120W) being as high as 20% for one of the meters in H09 and H37 and as low as 1.1% in H42. As the error varies from one device to another and is different for each power load, this is simplified in the analysis, and the error is considered to be 10% of the power load; this figure is supported by The electricity supply regulations (SI 1994, No.3021) which states that the tab voltage tolerance of 230V is within 6%, +10% (Buswell, 2013), the uncertainty is estimated and reported in Appendix A.

The calibration of the SMART PLUGs was performed by placing sensors in series, testing the following power loads: 40, 60, 90, 120, 1270 and 2520W. The SMART PLUGs error varies with power load and is different for each device. The error figure was simplified assuming a standard error of 10% of the load which was applied in the uncertainty calculation.

The calibration of PIRs and DOR sensors was performed against a 'HOBO Pendant Temperature Data Logger', which is a commercial waterproof, one-channel logger with 0.53℃ accuracy; the logger uses a coupler and optical base station with USB interface for launching and data readout by a computer. HOBO was calibrated with a thermostat, 'Thermo Scientific Laboratory Temperature Control Product', of which temperature stability is specified at 0.02℃ (Mason, 2010). The deviation error obtained from the calibration process varies from one device to another and one measurement to the next, being as high as 3.3% in one of the DOR sensors in H30 and as low as 0% in one of H46's DOR sensors.

The error in the gas measurement varied from 2.2% in H39 up to 5.5% in H09 compared with the meter readings. An average value of 3% is considered for the uncertainty analysis; this figure is also suggested by the statutory requirement for European meter accuracy (Electrical Energy Meters, 2002).

The hot water flow sensor was calibrated against metered flow water. Field test measurements were carried out at the beginning of the installation and when decommissioning. In the first test, a water measurement was recorded for each water flow meter; during decommissioning three tests were performed for high and low water flow. Metered water volume and temperature were compared with monitored water in order to estimate the accuracy of the data; the error ranged from 0% to 20%, although the uncertainty analysis is performed considering an average error of 3% for the simplification of the analysis, following the suggestion by the statutory requirements for European meter accuracy.

3.5.1 Pre-processing

Pre-processing of the raw data was carried out to check for missing data and data quality issues, analyse appliance end use consumption, estimate the temperature difference for the heat exchange calculation, account for PVs energy production as part of the energy supply in two households, and estimate the energy consumption for different heating systems and additional space heating units.

Treatment of missing data

The number of days when all the relevant monitoring channels were available ranged from 56 days in H09 to 246 in H46; H09, H37. H41 only had available data for part of the year; H09 had data from June 2013 to the end of the year, whereas H37 and H41 only had data up to September and August 2013 respectively. In order to have a comparable energy consumption annual estimation, a dataset of bi-monthly average values was created, to consider seasons and weekdays. Bi-monthly average values were used for the calculations, 12 profiles were created and used in the analysis, 6 weekdays and 6 weekend days over the year; H09, H37 and H41 were treated differently as H09 did not have data over the first heating season of the year, and H37 and H41 did not have data over the second; bi-monthly average values for the missing months were based on data from months when outdoor temperature was similar, i.e. H37 September-October profile was based on May-June average values. Figure 3.7 shows daily outside air temperature during 2013. Outside air temperature varies over the year and hence by using weekly profiles, every two months, the seasonal effects due to outdoor temperature can be captured in the analysis.

The coldest temperatures appear during the first heating season (from January to April 2013), which are colder than those in November-December 2013. The warmest temperatures appeared from April to November, showing even warmer temperature than those in spring. These observations are especially important when analysing the results. For example, in H09, available data only covered the warmer period of the heating season so annual space heating consumption is expected to be relatively lower than in the other samples; also, a slight deviation in the results is expected from H37 and H41, as space heating demand is influenced by missing data in the warmer heating season, and space heating consumption will be comparably higher.

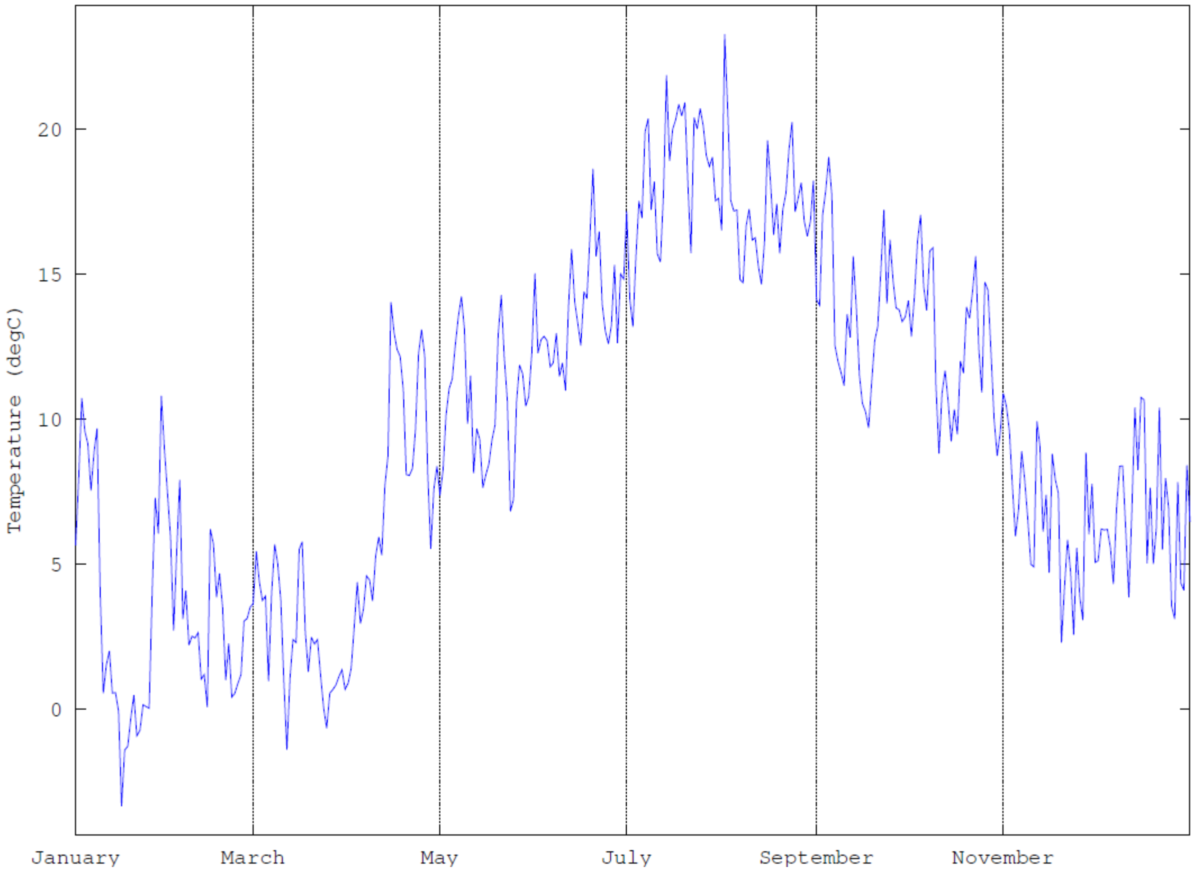

Figure 3.7: Daily outdoor air temperature over 2013 from MIDAS data.

For each two months of data, a weekday and a weekend day profile were created by averaging the results from the model over the number of available days within those months. Average whole house energy consumption by weekday is studied to identify any difference between days when the house is generally unoccupied and days when there are people at home, as is shown in Figure 3.8. Average whole house energy consumption shows slight differences; nevertheless, the differences between the use of end use appliances and lighting varies considerably with occupancy (Richardson et al., 2010) and so 2 bi-monthly profiles are used in the analysis, one for unoccupied days and one for occupied days.

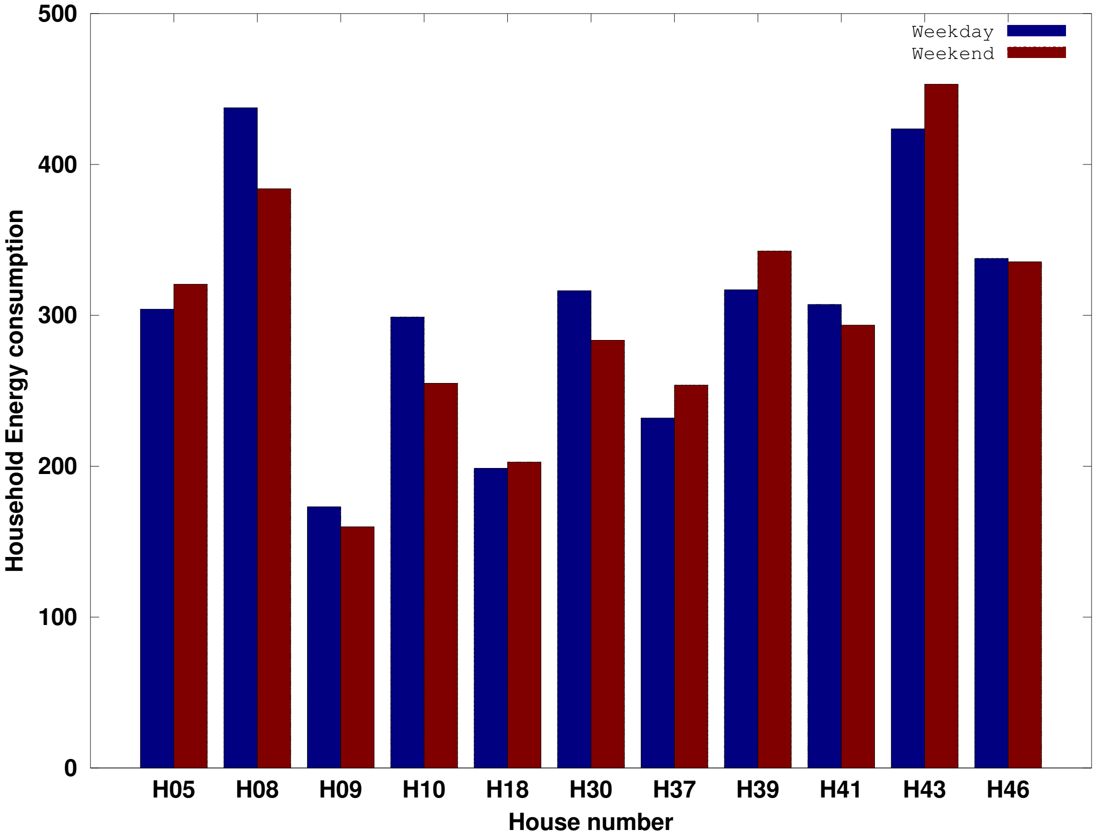

Figure 3.8: Weekday and weekend day average daily whole house energy consumption over 2013.

Estimation of the average indoor air temperature

Air temperature measurements were taken every two minutes; the number of monitored rooms in the sample households vary from 5 in H39 to 12 in H46 as it can be seen in Table 3.6. Daily average indoor temperature was calculated based on the number of available sensors for each day of data over the year. The daily average value was used to assess the heat exchange with the outside (Roulet, 2002). Although temperature data was available for more than one room in many sample days, the method applied uses an average indoor temperature. The method is applied following a single zone methodology, which simplifies the calculation approach and amplifies its usability, being applicable even if the number of sensors is limited. A single zone approach simplifies the heat exchange calculation, which is estimated between the inside and the outside of the building, using daily average air temperature to calculate heat exchange through the building fabric and ventilation over a 24 hours period.

In order to estimate the daily average indoor temperature for a given day, available temperature measurements were included in the calculation. The number of sensors recording data fluctuates from one day to another and in order to calculate the daily heat balance equation, the day was chosen if at least one temperature sensor had recorded data; if all measurements were missing for a given day, the day of data was rejected from the analysis. For days when at least one sensor was working, missing data from not working/connected sensors was replaced with available measurements from the hall to calculate the mean value. The selection of the hall data as a reference to replace missing data from other sensors followed two criteria: the first was that the temperature measurements from the hall were overall the most similar to the mean values between the room sensors, being generally lower than the living area but higher than the bedrooms; also, for consistency reasons, the hall was the only space that was monitored in every house.

Table 3.6: Number of temperature sensors installed

H05	**H09**	**H10**	**H30**	**H37**	**H39**	**H46**
9	11	7	12	11	5	12

The single zone approach and the use of a variety of sensors to calculate average indoor temperature impacts on the uncertainty of air temperature, the calculation of which is explained in Appendix A. Table 3.7 summarises the daily minimum, average and peak average temperature in the study houses over the heating period in 2013:

Table 3.7: Daily average temperature figures based on available measurements indoors (Over 24 hours).

Household number	**Average (℃)**	**Minimum (℃)**	**Maximum (℃)**
H05	18.2	15.2	20.8
H09	17.4	15.6	19.6
H10	19.1	18.9	19.8
H30	16.9	11.5	18.7
H37	18.2	8.7	20.0
H39	16.9	13.2	20.0
H46	20.7	18.9	22.3

Average indoor temperatures, which are calculated based on all the available sensors over a 24 hours period, show temperatures ranging between 17 and 19℃, except for H10 and H46, which show higher average temperatures, between 19 and 21℃. Minimum temperatures are as low as 8℃ in H37, which was recorded over a period when the property was unoccupied and the heating was off for more than a week. H30 also shows a low minimum temperature, which is linked to unoccupied periods of time and it is believed to be influenced by high fabric heat losses due to the solid wall envelope and lack of loft insulation. The maximum daily average temperature is as high as 22.3℃, and it appears in H46, which may be because an older adult is part of this extended family. The variation between minimum and maximum temperature within households is from less than 1℃ in H10 to more than 11℃ in H37. There are a number of factors impacting on the daily average indoor temperatures that can explain the broad range of temperatures; for instance: occupancy during the day, space heating settings, insulation levels and infiltration or opening of windows and doors.

Heat exchange between the inside and the outside is calculated as in Equation 3.1 by considering the daily average indoor temperature ‘T_{in}’ and the daily average outdoor temperature ‘T_{out}’ from the DOR sensors. The uncertainty from the DOR sensors is explained in Appendix A.

$$\Delta T = T_{out} - T_{in} \tag{3.1}$$

Treatment of homes with PV generation

CT monitoring devices were used to quantify total electricity consumption in the sample of dwellings. H09 had PV panels installed, and hence monitoring the incoming supply led to the consumption and generation being monitored. In this case, the second meter installed to monitor generation was used to disaggregate the actual consumption. The assumption underpinning the pre-processing of the data is that if the production of electricity from photovoltaic panels is higher than the power consumed by the dwelling, the electricity is sent to the grid, whereas if it is lower, the house is supplied with a mix of electricity produced by photovoltaic panels and electricity from the supplier.

Space heating and hot water systems

The energy source and the system supplying space heating, cooking and hot water varied from house to house. Some households had electric ovens, hobs, showers and boilers, whereas others had gas appliances or a combination of gas and electric. For example in H41, one of the showers is electric and the other is supplied by the main heating system, the boiler. Each combination of technologies needs a different treatment for the assignment of energy to space heating, hot water and cooking.

Tank (T) and combination boilers (C) provided central space heating and hot water; and in some houses additional heating systems complemented the main heating system, such as the underfloor heating in H30, an electric radiator in a detached studio placed in H43 and an electric heating fan in H09. Also, some houses made use of open fires ventilated by chimneys to heat the living room on special occasions, for example H05 and H10, as listed in Table 3.8. The energy generated by the use of open fires is not considered in the analysis, as it was not measured, and it was not possible to identify when it was in use; the unmeasured energy source generates uncertainty in the approach as it impacts on the energy balance.

Table 3.8: Heating system characteristics.

Household	**Boiler type**	**Additional heating**	**Hob**	**Oven**	**Electric shower units**
H05	Combi	✓	Electric	Electric	0
H09	Combi	✓	Gas	Electric	1
H10	Combi	✓	Gas	Gas	0
H30	Combi	-	Gas	Electric	0
H37	Combi	-	Gas	Electric	1
H39	Combi	-	Gas	Gas	1
H46	Combi	-	Gas	Electric	0

3.6 Qualitative data

Interviews were performed in participants' homes and took place when the energy reduction analysis was finished, and graphs were ready for their presentation to participants, between the end of September and the end of October 2014 at the participants' convenience. Interviews varied from 1 hr : 16 min to 2 hr : 33 min in length and comprised a set of two activities and 15 semi structured interview questions, with both closed and open ended questions that, provided opportunity for discussion as further explained in Chapter 7.

The face to face semi-structured interviews were tailored for each specific household. A semi-structured format was chosen to allow adjustment of questions for different case studies, to encourage discussion amongst family members and to frame each household case study (Robson, 2011; Vadodaria et al., 2010; Coughlan et al., 2013). Families were interviewed in their own homes to help foster a relaxed atmosphere, for the convenience of householders and to to enhance the recollection of routines and practices often automatized by householders (Stanton et al., 2014).

The interview was designed in three main parts: contextualisation, task and discussion. The objective of the interview was to understand which measures participants were willing to apply in their home, as well as their reasons for rejecting specific reduction measures. The interview was designed to answer the main research question, contextualising and analysing it by assessing the following issues:

- understand householders previous knowledge about possible energy reduction measures;
- identify householder perceptions of the energy reduction potential of a range of intervention strategies;
- rank which measures householders are willing to apply;
- establish barriers preventing participants from reaching reductions;
- describe drivers and opportunities for future energy savings; and,
- list measures that would effectively reduce energy in the home.

The data from the interviews was transcribed and analysed using a thematic analysis technique as described in Chapter 7.

The flow chart in Figure 3.9 presents the research questions driving the interview. For each reduction measure, participants were asked about their previous knowledge of that measure, their willingness to apply that measure in the home, their perceived barriers preventing its application (if any), any technology that could help them to achieve it and under which contextual circumstances it would be possible to apply that reduction in the future; and to then evaluate acceptable measures and the barriers stopping householders from applying them.

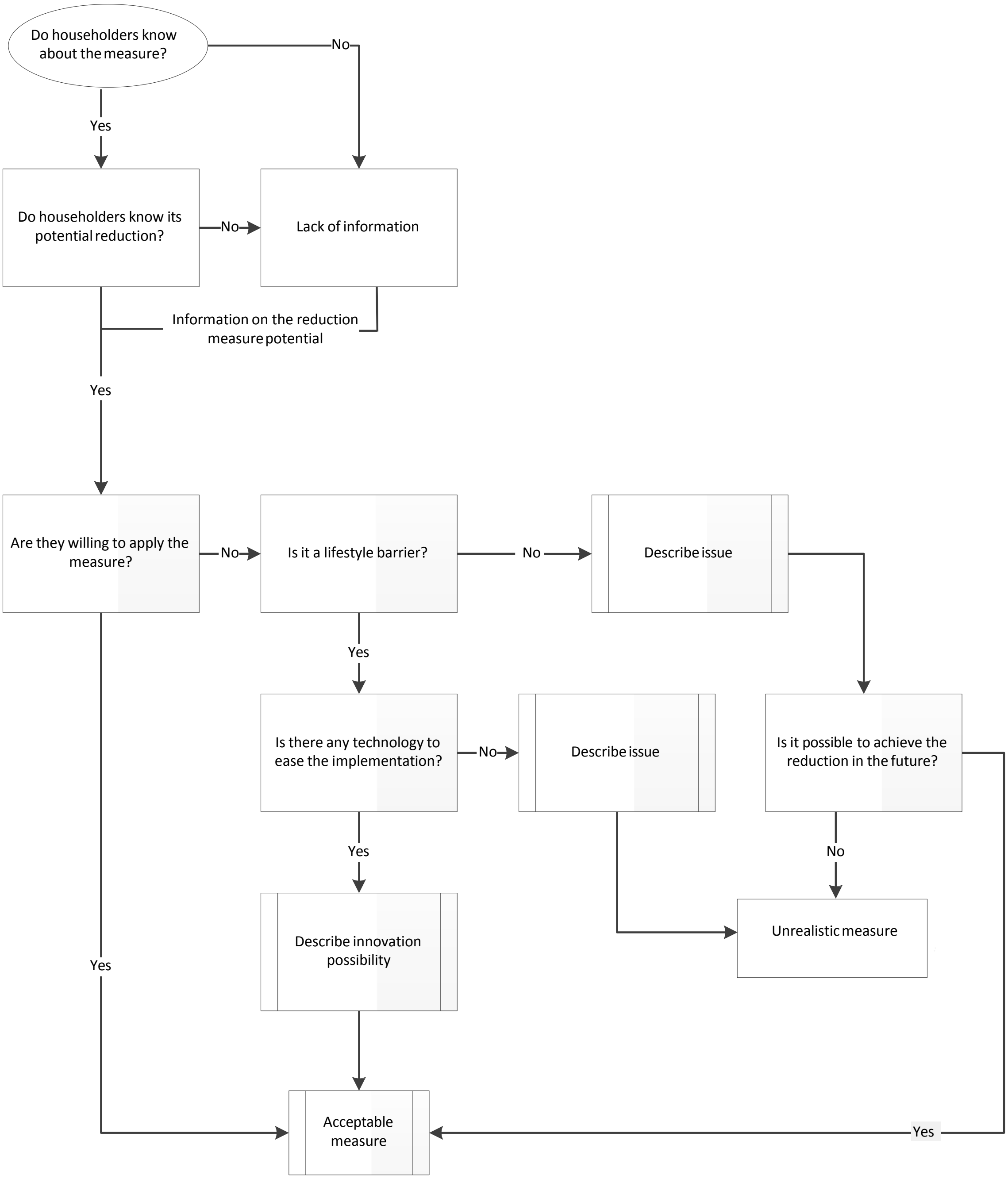

Figure 3.9: The research question flow chart used in household interviews.

3.7 Socio-technical evaluation

The results from the interviews were analysed and interpreted to build a hypothetical 2050 scenario which quantifies the impact of measures accepted by householders; unrealistic assumptions applied in the reduction model were corrected and barriers which needed to be overcome in order to reach reductions were discussed. Also, the role of smart home technology to achieve reduction measures was evaluated and discussed. Details on the application of the combination of methods is explained in Chapter 7.

3.8 Summary

This chapter introduces the socio-technical framework applied, justifying the approach and presenting the selected sample of family homes for the evaluation. General methodological aspects are explained, including the sample selection criteria, the ethical considerations, the quantitative data collection performed, the data characteristics and its pre-processing. The qualitative data collection and analysis is also presented at a high level, introducing the socio-technical analysis performed after the application of both techniques; further details are provided in Chapter 7. Also, modelling details are explained in Chapter 4 and the approach to quantifying reduction measures is presented in Chapter 5.

This chapter accomplishes the Objective 2 set in Chapter 1 by developing a research framework that assesses the impact of reduction measures on specific households and that evaluates the suitability of a set of measures against the lifestyles and preferences of the occupants.

Chapter 4

Household energy modelling

In this chapter, modelling methods are reviewed, and an approach is developed in order to calculate a daily heat balance in the dwellings of study based on monitoring data. The approach combines the data with assumptions about dwelling characteristics to yield a residual that is attributed to the air change rate. These values are used to create a ventilation model, that can be re applied to the heat-balance model in order to predict gas consumption under different scenarios. The uncertainty of the calculated ventilation rates is given in Appendix A.

4.1 Review of modelling methods

Modelling techniques have been used over the years to calculate the energy consumption needed in buildings. Swan and Ugursal classify the approaches used in building energy studies differentiating between top-down and bottom up models, as shown in Figure 4.1. Top down models aggregate estimated national residential energy consumption by attributing characteristics of the entire housing stock, whereas bottom up methods estimate energy consumption of individual or groups of buildings, for which results can be extrapolated (Swan and Ugursal, 2009).

Bottom up models require higher detailed input data but enable the analysis of energy conservation measures (Shorrock and Dunster, 1997; Swan and Ugursal, 2009). Bottom up models can apply 'engineering', 'statistical', 'hybrid' or 'artificial intelligence' based approaches (Swan and Ugursal, 2009) although hybrid and artificial intelligence approaches are not as developed (Hai-Xiang et al., 2012).

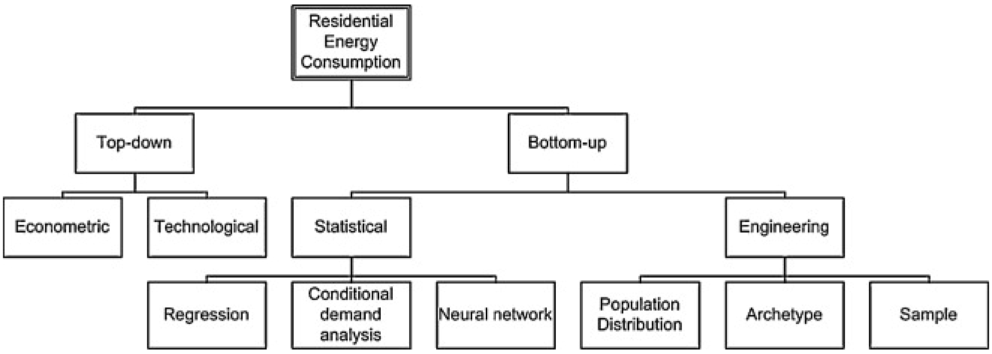

Figure 4.1: Residential energy models, (Swan and Ugursal, 2009).

Statistical models correlate energy consumption with dependent variables and can be applied to billing and survey data (Swan and Ugursal, 2009). These models rely on regression techniques and are useful to explain the effects of occupant behaviour, as suggested by previous studies (Haldi and Robinson, 2011; Wood and Newborough, 2003), although the main limitation of these models is their poor performance in predicting the impact from energy conservation interventions (Swan and Ugursal, 2009; Kavgic et al., 2010; Richardson et al., 2010).

Further methodologies, such as hybrid methods, also called 'grey' models, constitute an option for systems where part of the behaviour remains unknown or there is incomplete data, being a mix between statistical and engineering models (Wang et al., 1999; Guo et al., 2011; Zhou et al., 2008). Nevertheless, these are complex methods to implement and the uncertainty associated with the results is considerably high.

Artificial intelligence based approaches are capable of solving non-linear problems, even though, their results are similar to engineering based approaches and given their complexity they are not the most recurrent option (Neto and Fiorelli, 2008).

4.1.1 Engineering models

Engineering models have been widely used for the analysis of building performance (Cheng and Steemers, 2011) and the impact of reduction measures, having a relevant role in supporting energy policy and public building design. Dynamic thermal models can simulate up to 1 minute time resolution. These models, for example, the response transfer 'RT', or the conduction transfer function 'CTF' use very detailed physical functions to estimate building energy requirements based on building characteristics at each time interval, requiring a large amount of input data. Simplified dynamic models such as the harmonic (Mackey and Wright, 1944) and the Resistance-Capacitance 'RC' model constitute an option for up to hourly resolution energy consumption analysis. The harmonic methodology is based on boundary conditions, for instance, periodic functions used for the calculation of energy conduction through the fabric, even though it has been criticised for its performance (Peng and Wu, 2008). RC models are based on the analogy between electric loads and heat transfer and are broadly used; the International Standard for the space conditioning and cooling calculation is a 5 resistance 2 capacitance approach (ISO, 2008).

Dynamic thermal modelling tools such as DOE-2, EnergyPlus, BLAST, ESP-r or TRNSYS are globally used for the assessment of building energy demand (DoE, 2012; U.S Department of Energy, 2015; Birdsall et al., 1990; University of Wisconsin–Madison. Solar Energy Laboratory and Klein, Sanford A, 1979).

Simpler engineering models have also been used in building energy research in the last 30 years, such as BREDEM, UKDCM or the Community Domestic Energy Model 'CDEM' in the UK; these are broadly applied for monthly and annual estimations (Henderson and Hart, 2007; Jones et al., 2001; Rylatt et al., 2003); for instance, the 40% house national housing scenarios (Boardman et al., 2005) were developed by using the UKDCM.

The main limitation of applying either steady-state or dynamic models is the number of assumptions, that determine the output energy requirement, when in reality energy consumption in the home is tightly bound to the inhabitants (Malkawi and Augenbroe, 2004; Firth et al., 2008; Zimmermann et al., 2012; Kashif et al., 2013). It has been recognised that the input profiles driving current models are poor, especially with respect to simulating behavioural variables, that are not as relevant in commercial dwellings but are crucial in domestic buildings. For example, BREDEM defaults standard indoor temperature settings of 21℃ to calculate the energy consumption in dwellings where the space heating is controlled with a management system, and an increasing temperature value for houses with no space heating controls. Assumptions also apply to heating times, ventilation rates and to the use of miscellaneous appliances; BREDEM, for example, estimates the ventilation rate by calculating an infiltration figure, assuming that when there is no mechanical ventilation system, occupants deliberately ventilate the dwelling if the infiltration rate is less than one air change per hour; this assumption can misrepresent current ventilation routines, misleading potential opportunities for energy reduction from family lifestyle patterns. Poor assumptions can result in unrealistic estimations of the impact achievable from reduction measures, which when taken into account in energy policy making can lead to retrofit installations being recommended that are expensive and disruptive for householders, but do not achieve the expected results (Behavioural Insights Team, 2011; Hong et al., 2006).

The potential of ventilation practices to reduce energy consumption is one of the overlooked areas of research, and as published work affirms, natural ventilation through the opening of windows and doors depends on user choice and heavily impacts on ventilation rates and on final energy consumption (Bek et al., 2011; Howard-Reed et al., 2002).

4.1.2 Modelling occupant behaviour

The number of behavioural variables contributing to final household energy demand results in a complex system, especially for space heating, which is not directly driven by occupancy and for which settings depend mostly on occupant choices linked both to thermal comfort and system control. The main parameters considered for the determination of energy demand profiles in design and modelling tools are based on fabric heat loss: building type and building thermal behaviour; heat production: heating system type and efficiency; electricity consumption: appliance ownership, efficiency, lighting usage and bulb type; heat loss through ventilation: cold air infiltration and assumed ventilation rates for natural ventilation; and other variables which depend on householder choice, and impact upon energy consumption. These include but are not limited to: system control and thermostat settings, occupancy, temperature choice, natural ventilation and hot water consumption for showers and taps (Summerfield et al., 2007; Boait et al., 2012; Gram-Hanssen, 2010; Santin, 2011; Santin et al., 2009; Guerra-Santin and Itard, 2010; Shipworth et al., 2010).

The reduction measures analysis is limited by the dearth of hard data with which to develop and validate these models, taking into account occupant behaviour. This difficulty in collecting real data has produced an over reliance on theoretical predictions for many years (Oreszczyn et al., 2006; Cheng and Steemers, 2011; Natarajan et al., 2011). Although there are studies which have developed behavioural variables, there is still much work needed to systematically represent observed human behaviour and the way people actually live in the home environment (Bourgeois et al., 2006).

The challenge of building energy analysis is to move beyond controlled activity profiles and predefined scenarios towards prediction tools that account for the complexities of everyday life (Porteous et al., 2012; Malkawi and Augenbroe, 2004; Firth et al., 2008; Zimmermann et al., 2012). Human behaviour has been accounted for in simulation studies through the notion of 'lifestyle constraints', considering individuals' consumption as the result from a range of contextual factors, such as building type, appliance characteristics, lifestyle choices, work, school and leisure, and the social and cultural values that are placed on daily activities (Kashif et al., 2013; Haldi and Robinson, 2011; Wall and Crosbie, 2009; Porteous et al., 2012; Wilhite et al., 1996). A consideration of lifestyle constraints has important implications for understanding the domestic context, given that it shows the complexity and number of variables that might interact to determine how energy is consumed. While building simulation tools require an element of simplification, there is an increasing need to represent patterns and interrelations that go beyond the consideration of individuals (Herkel et al., 2008; Toftum, 2010) and individual appliance use (Richardson et al., 2008), and instead take into account wider practices such as ventilation routines or space heating control (Hughes et al., 2009). More comprehensive and sophisticated models are needed to prevent the kinds of forgone conclusions that derive from narrowly defined notions of causality, especially for the design of future energy reduction measures in the home whose effectiveness will be highly influenced by users' everyday choices (Kane et al., 2015).

4.1.3 Ventilation

Current models do not offer a good representation of ventilation rates in occupied dwellings (Hoes et al., 2009). So far, studies aiming at implementing realistic ventilation behaviour patterns in simulation programs have been focused on occupant behaviour in office buildings (International Energy Agency, 2013). This becomes problematic when tailoring information to home owners and estimating the impact of retrofit measures on energy consumption for specific households. Air change rates have a significant impact on building energy consumption, and the energy use linked to householders' habits on natural ventilation can be over/underestimated using modelling tools, which relies on a limited number of inputs to assess how people ventilate the house (Henderson and Hart, 2007).

The air change rate N is a measure of the air volume added or removed from a space. It is an absolute value relative to the volume of space and it is calculated in existing models by assuming a number of Air Change Rates (ACH) based on an estimation of the dwelling infiltration rate, occupant window openings and minimum health standards for ventilation. Current models rely on poor assumptions to estimate the air change rate, as this value is highly dependent on occupants' behaviour, especially in domestic dwellings (Henderson and Hart, 2007; Jones et al., 2001; U.S Department of Energy, 2015; Birdsall et al., 1990; University of Wisconsin–Madison. Solar Energy Laboratory and Klein, Sanford A, 1979).

Empirical ventilation studies have shown behavioural parameters to be strong predictors (Bek et al., 2011; Howard-Reed et al., 2002). Howard-Reed found that the highest building ACH variability, was given by the opening of windows (Howard-Reed et al., 2002); In further research, Howard-Reed, reported that 63% of the average air change rate in 16 Denmark homes was due to occupants opening windows and doors (Howard-Reed et al., 2002). Also, householder characteristics such as age, gender and comfort preferences have been found to be influences upon ventilation actions, as well as building characteristics and type of room. For example, bedroom windows are more frequently opened in domestic buildings. Further to that, occupants' ventilation behaviour is strongly determined by climatic variables and routines; for example, a number of studies found correlation between the number of openings and the season, time of the day, outdoor temperature, solar radiation and wind velocity (International Energy Agency, 2013).

4.2 Model justification

Engineering models have widely been used to assess energy conservation studies. Current modelling tools offer a calculation approach to estimate energy consumptions in dwellings, but they are designed to estimate energy consumption based on a high number of assumptions based upon typical user patterns and behavioural parameters. The customization of existing tools to input monitoring data is time consuming and limited by the calculation equations and assumptions within the tools, whereas the use of simple steady-state heat balance calculations simplifies the use of monitoring data and the adaptation of assumptions to the case study. The approach can be used to tailor energy reduction studies as energy data becomes available.

The development of the heat balance model described in the section below enables the analysis of tailored monitored data for space heating, hot water and electricity to estimate reductions based on households' patterns of consumption, implicitly accounting for the occupant behaviour. The model aims to characterise the dwelling energy consumption, improve the input parameters for the estimation of ventilation heat loss and establish a framework for analysing household tailored reductions.

4.3 The heat balance approach

The calculation approach is based on a simple steady-state relationship that assumes: the heat gain in the space is that from the space heating, the hot water consumption, the heat produced by the appliances, the occupants body heat and the solar gains; the heat loss (for higher temperature indoors than outdoor) is that from the fabric and the hot water leaving the space; and the residual energy in the heat balance is attributed to ventilation,

$$Q_v = Q_{sh} + Q_{w_{use}} + Q_e + Q_p + Q_s + Q_{w_{loss}} + Q_f \tag{4.1}$$

where Q_v, Q_{sh}, $Q_{w_{use}}$, Q_e, Q_p and Q_f are the daily values of heat for ventilation, gas combustion for space heating and hot water production, electricity consumption, gains from people, solar gains, hot water evacuation and heat loss through the fabric, respectively in MJ. Monitored data was used in the calculations together with assumptions and estimates for unmeasured parameters such as wall conductivity.

This approach is a unique application of the heat balance as it uses household specific data to calculate the variables to tailor the energy balance to a specific home. The uncertainty of the estimates is presented in Appendix A, and the output ventilation rate is validated in Section 4.4.

Solar gains

Solar radiation is a source of heat in dwellings, especially in the summer. Solar gains enter the space through the envelope by convection, both through the glazing and walls. Steady-state models used in the UK, such as BREDEM, neglect heat gains from walls, as they are not significant during the winter months when most energy for space heating is used (Henderson and Hart, 2007). In this study, solar heat gains are calculated following the BREDEM approach.

Parameters used within the calculation are summarised in Table 4.1; these have been either assumed from published values, monitored or derived from a combination of inspection and self-reported information.

The glazing frame factor is assumed to be 80% of the windows area. The glazing factor is chosen from published values in CIBSE; these vary with glazing type and are listed in Table 4.2. The solar access is assumed from BREDEM for households where outdoor objects stopping the sunlight are unknown; solar declination values are applied to each month of the year following published values from BREDEM; the vertical solar flux is calculated by applying correction factors for each month of the year; these are A, B and C and are calculated as in Equations 4.5, 4.6 and 4.7. Measurements of daily solar radiation are used in the equation.

Table 4.1: The parameters of the solar gain model implemented in the BREDEM approach.

Description	**Parameter**	**Type**
Solar heat gains	Q_s	Calculated
Vertical solar flux	Fx	Calculated
Conversion factor	$Rhtov_q$	Calculated
Solar Radiation	R_s	Monitored
Frame Factor	FF	Assumed
Solar Access	SA	Assumed
Glazing transmission factor	G_f	Assumed
Windows area	A_w	Measured
Orientation	q	Calculated
Latitude	f	Calculated
Monthly solar declination	d_{month}	Calculated

$$Q_s = FF \cdot SA \cdot 0.9 \cdot Fx \cdot G_f \cdot A_w \tag{4.2}$$

$$Fx = Rhtov_q \cdot R_s \tag{4.3}$$

$$Rhtov_q = A + B \cdot cos(q) + C \cdot cos(2q) \tag{4.4}$$

$$A = 0.702 - 0.0119(f - d_{month}) + 0.000204(f - d_{month})^2 \tag{4.5}$$

$$B = -0.107 + 0.0081(f - d_{month}) - 0.000218(f - d_{month})^2 \tag{4.6}$$

$$C = 0.117 - 0.0098(f - d_{month}) + 0.000143(f - d_{month})^2 \tag{4.7}$$

Table 4.2: Values for Glazing factor (G_f) for different glazing types.

Glazing	**Factor**
Single	0.85
Double	0.72
Secondary glazing	0.76
Triple	0.64

Internal gains from appliances

The incoming main power consumption is used as an input to calculate heat gains in the house. Power is assumed to be converted to heat gains, except for the shower, where it is assumed that only a quarter of the consumption results in a gain into the space, as suggested by The Governments Standard Assessment Procedure for Energy Rating of Dwellings (SAP BRE, 2012). This is a simplification of the heat transfer mechanism, which is applied assuming that heat is reabsorbed during the day, when in reality the convective portion of heat from the electric equipment is instantaneously absorbed, and the radiant portion of the heat is firstly absorbed by the building elements surfaces and then dissipated over time increasing air temperature (Hosni et al., 1999). Table 4.3 summarises the parameters considered in the calculation.

Table 4.3: Electric energy parameters.

Description	**Parameter**	**Type**
Electric input	Q_e	Calculated
Electric shower input	Q_{es}	Calculated
Power	P	Monitored
Shower power	S_P	Monitored
Heat rate	H_r	Assumed
Conversion factor	WMJ	Calculated

$$Q_e = H_r \cdot P \cdot WMJ \tag{4.8}$$

$$Q_{es} = 0.25 \cdot S_P \cdot WMJ \tag{4.9}$$

Occupancy gains

In the Heat Balance Model, gains from occupants are calculated based on a standard metabolic rate, which is assumed to be 100 Watts for male adults; female adults are assumed to produce 15% less than males, and children 25% less (ASHRAE, 2001). The human body produces a mix of sensible and latent heat, which increases with degree of activity (The Chartered Institution of Building Services Engineers, London, 2006). Latent heat is assumed to be instantaneously gained into the space, whereas sensible heat is absorbed over time, being 70% radiant heat. The model assumes that over the span of one day, 100% of occupants' heat is reabsorbed into the space based on previous work (Hosni et al., 1999). Table 4.4 summarises the parameters considered in the calculation. Occupancy profiles are generated for each house based on the information collected via initial visits and later discussion with participants, creating three occupancy schedules:

- weekday, house occupied by the whole family for 16 hours; for part time employees, house occupied during 20 hours, schedules vary depending on each household's timetable;
- working from home, house permanently occupied by one or more family member during working hours and by the whole family for 16 hours; and,
- weekend, house permanently occupied by the whole family, which represents the worst case occupancy profile.

Table 4.4: Variables considered in the body heat calculation.

Description	**Parameter**	**Type**
Body heat gains	Q_p	Calculated
Occupants	N_O	Reported
Time in	t_i	Reported
Metabolic rate	M_r	Constant
Conversion factor	WMJ	Calculated

$$Q_p = M_r \cdot N_O \cdot t_i \cdot WMJ \tag{4.10}$$

Space heating

Central space heating and hot water is supplied by gas fired boilers; in some dwellings, the hob and/or oven is also fired by gas. The gas energy consumption is calculated based on the monitored volume of gas and the calorific value, which is assumed from the National Grid supplier to be 39500 J/m^3 (National Grid, 2011).

The boiler efficiency is assumed from the SEDBUK database (Home Heating Guide, 2014), for each boiler model, although the boiler efficiency varies depending on the installation, usage, maintenance, age and season.

Hot water volume boiler inlet and outlet water temperature are monitored and are converted to volume of gas needed to heat the water to the given temperature, assuming water density ρ and heat capacity Cp_w. Water density is assumed to be constant at 1000 kg/m^3. Water heat capacity is assumed to be 42000 J/kg℃.

Space heating consumption is estimated by applying the difference between total gas consumption and gas use for hot water. The parameters used within the calculations are listed in Table 4.5. Gas loads from the oven and hob are accounted for as part of the space heating gains, as the majority of the hob and/or oven input is converted into heat gains. In the summer months when space heating is off, daily gas consumption is attributed to cooking loads.

Table 4.5: Space heating variables considered in the calculation.

Description	**Parameter**	**Type**
Space heating heat gains	Q_{sh}	Calculated
Gas consumption	Q_g	Calculated
Gas Volume	V_g	Monitored
Gas Calorific value	$C_{v_{gas}}$	Assumed
Hot water consumption	$Q_{w_{use}}$	Calculated
Incoming water temperature	Tw_{in}	Monitored
Outgoing water temperature	Tw_{out}	Monitored
Water volume	V_w	Monitored
Water mass	m_w	Calculated
Water density	ρ	Assumed
Water heat capacity	Cp_w	Assumed
Boiler efficiency	ϵ	Assumed

$$m_w = V_w \cdot \rho \tag{4.11}$$

$$Q_g = C_{v_{gas}} \cdot V_g \cdot \epsilon \tag{4.12}$$

$$Q_{w_{use}} = (Tw_{out} - Tw_{in})m_w \cdot Cp_w \tag{4.13}$$

$$Q_{sh} = Q_g - Q_{w_{use}} \tag{4.14}$$

H30 and H43 had additional heating systems treated thus:

- add the underfloor heating loads from H30s bathroom to space heating, and;
- deduct the electric loads from the electric heater in H43 studio, as this is detached to the main house.

Hot water input

The energy consumption needed for heating the water volume to the output temperature is calculated on a minutely basis to track the temperature rise in the pipe when hot water is supplied by applying Equation 4.13. The parameters used within the calculations are listed in Table 4.6.

For tank systems, which experience water heat loss over time, the energy consumption is calculated as in Equation 4.15, following experimental work by (Simpson and Castles, 1992; Buswell et al., 2013). The tank volume of water is assumed at a standard capacity of 120 litres, and ΔT^1 between ambient temperature and hot water is assumed to be kept at 50℃, assuming that cold water inlet remains at 10℃ and hot water delivery at 60℃. (Henderson and Hart, 2007).

$$Q_{t_l} = 2.748 \cdot \Delta T \tag{4.15}$$

The heat output from the hot water leaving the house is calculated as in Equation 4.16. The temperature of the drained hot water is assumed at 18℃, considering ambient conditions to be between 18℃ and 25℃ (Buswell, 2013);

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[1] ΔT: Temperature difference

Table 4.6: Hot water variables considered in the calculation.

Description	**Parameter**	**Type**
Hot water volume	V_w	Monitored
Hot water heat loss	$Q_{w_{loss}}$	Calculated
Water heat capacity	Cp_w	Assumed
Water final temperature	Tw_f	Assumed

$$Q_{w_{loss}} = (Tw_{out} - Tw_f)V_w \cdot Cp_w \tag{4.16}$$

Building fabric

Heat is conducted from and to the dwelling through the building fabric. The thermal transmittance values used in the analysis are summarised in Table 4.7 and were assumed from building regulations, the CIBSE guide and previous work as explained in detailed below, based on the characteristics of the building elements, i.e. the existence of insulation, its material, thickness, size and the dwelling year of construction. The variables considered in the heat loss calculation are presented in Table 4.8.

The U value for insulated cavity walls is assumed from previous work by (Beng, 2003). Figures are based on the thermal performances which satisfy Building Regulation requirements at the dwelling year of construction. Insulated cavity walls built prior to 1990 are assumed to have an external wall U-value of 0.6 W/m^2K, and those built after 1990 are assumed to have a U value of 0.45 W/m^2K.

The U value for uninsulated cavity walls is assumed to be 1.36 W/m^2K. The thermal performances of these walls were estimated by (Beng, 2003) based upon figures contained within CIBSE Guide A3 (The Chartered Institution of Building Services Engineers, London, 2006).

The U value for solid walls is assumed to be 2.12 W/m^2K following work by (Beng, 2003). This value is based on data from the 1991 English House Condition Survey (DoE, 1996), which indicates that the majority of solid walls thickness in the UK is 9 inches (approximately 225 mm).

In order to establish the typology of the ground floor for dwellings where no information was available, the assumption was that all dwellings built prior to 1939 had suspended timber ground floors, whilst all dwellings built after 1939 had solid concrete ground floors. The assumption was double checked with participants where possible.

The U-value for suspended timber ground floors is assumed to be 0.80 W/mK, which are considered to be uninsulated due to the building regulations at the year of construction (DoE and OFFICE, 1994). Solid ground floors built before 1990 are assumed to be uninsulated whereas dwellings built between 1990 and 1995 have an assumed ground floor U-value of 0.45 W/mKand those built after 1996 0.35 W/mK.

The roof U value is based on the roof accessibility and its insulation thickness. The U value for uninsulated accessible roofs is assumed at 2.02 W/m^2K; a range of insulation thickness is summarised in Table 4.7 based on published values of pitched roofs insulated at the ceiling level (The Chartered Institution of Building Services Engineers, London, 2006).

Windows U values are assumed considering the number of glass units. Single glazed units were found in H30, where frames were made of timber, assuming a U value of 4.7 W/m^2K. Other households have a mix of single and double glazed windows; this is the case for H05 and H39. The U value for double-glazed windows with UPVC frames was assumed at 3.3 W/m^2K. (Beng, 2003).

The door U values vary depending on the existence of glazing and its area. Solid timber doors, half of which single-glazed, are assumed to have a U value of 3.7 W/m2K; doors with no glazed area have a U value of 3 W/m^2K (Beng, 2003).

The energy transmittance between semi-detached dwellings, i.e. H05 and H46, was neglected in the analysis, assuming that attached buildings were also heated.

The U-value of an element next to an unheated space, also called sheltered U-value, is approached in the calculation by modifying the element U-value as suggested in the SAP procedure (SAP BRE, 2012).

$$UW_{garage} = \frac{1}{\frac{1}{UW_{party}} + Ru} \tag{4.17}$$

$$Q_f = A_f \cdot U_f \cdot \Delta T \tag{4.18}$$

Table 4.7: Building elements: U values.

Building element	**Construction**	**U value** (W/m^2K)
Envelope	Insulated Cavity $\leq$ 1990	0.6
	Insulated Cavity $\geq$ 1990	0.45
	Solid Brick	2.12
	Cavity Wall	1.36
Ground floor	Suspended timber ($\leq$ 1939)	0.8
	Solid concrete slab ($\leq$ 1995)	0.45
	Solid concrete slab ($\geq$ 1995)	0.35
Roof	Accessible loft, Not insulated	2.02
	Accessible loft, $\leq$ 100mm	0.36
	Accessible loft, $\leq$ 250mm	0.16
	Not accessible loft, $\leq$ 50mm	0.51
Windows	Single glass, 10% timber frame	4.7
	Double glass, 10% UPVC	3.3
Door	Solid wooden door	3
	Half single glass door	3.7

Table 4.8: Fabric heat loss: Variables considered in the calculation.

Description	**Parameter**	**Type**
Building element energy exchange	Q_f	Calculated
Building element area	A_f	Calculated
Building element transmittance	U_f	Constant
Garage transmittance	UW_{garage}	Calculated
Party wall transmittance	UW_{party}	Constant
Temperature difference in-out	ΔT	Monitored
Heat loss through conductivity	Q_{cond}	Calculated
Dwelling floor area	A_{dw}	Calculated
Effective thermal resistance of unheated space	R_u	Selected

The accuracy of the fabric heat loss calculation is highly sensitive to the U-values applied in the calculations. Heat through the fabric is one of the main heat processes of heat exchange within the house, especially when the heating is on and ΔT is high. Assumptions about these variables can be the source of important differences between modelled and real energy dynamics in buildings, which in this case will influence Q_f and the model dependent variable Q_v. The use of assumed U-values is a limitation of the method, as the value might vary with real property conditions as reported in empirical studies (Energy Saving Trust, 2008b; Li et al., 2015).

4.4 Treatment of ventilation

In order to estimate the daily mean ventilation rate, Equation 4.1 is applied, assuming that Q_v is the residual from the calculation. Q_v is then used to estimate the air change rate, N, which is calculated as in Equation 4.19:

$$N = \frac{3 \cdot Q_v}{V_{house} \cdot \Delta T \cdot WMJ} \tag{4.19}$$

where ΔT is the temperature difference over 24 hours, and V_{house} is the house volume. The approach is inherently sensitive to the temperature measurements, as the internal and external temperatures approach each other, the evidence to estimate the ventilation rate reduces. Hence, the approach is only applicable when there is a reasonable difference of temperature between the inside and the outside.

In order to determine a sensible threshold for the minimum temperature difference acceptable in the calculation of the uncertainty of N, this was evaluated for every day worth of data. The analysis was based on propagation through the determining equations and details are given in Appendix A.

The uncertainty value in each parameter was evaluated each day in the analysis in combination with ΔT figures and the estimation of N generated by the heat-balance model. The upper plot in Figure 4.2 shows the daily ΔT in H05 for 2013; the data was evaluated against three thresholds, 2℃ (red line), 5℃ (blue line) and 10 ℃ (green line). As it can be seen in the graph, ΔT values under 5℃ only appear in the summer season, when the space heating is off; during the heating season, ΔT values range from 5℃ to 20 ℃ .

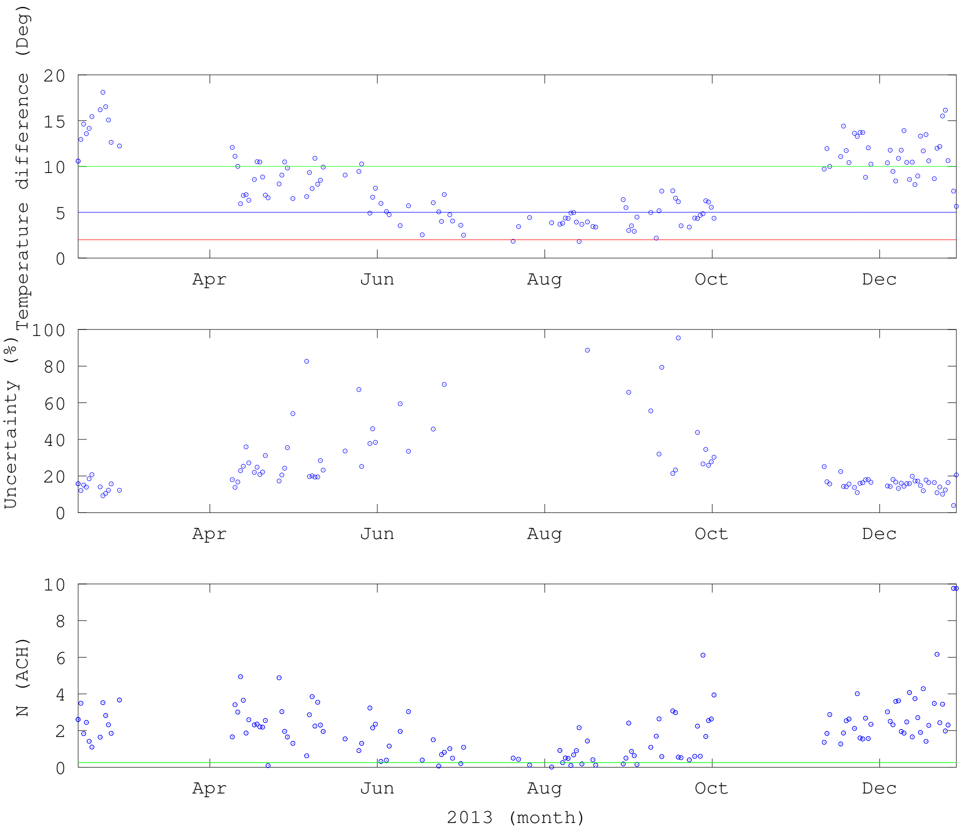


Figure 4.2: H05 N Annual results, N uncertainty and ΔT thresholds.

The second plot in Figure 4.2 shows uncertainty in the daily mean values of N. In H05, the uncertainty in N increases during the summer season, when the space heating is off and ΔT is below 5℃. During this period the uncertainty can be large and the estimates of N fall under the minimum daily figures that can be expected for infiltration in domestic dwellings, graphed in the third plot in Figure 4.2 with a green line (Hall et al., 2013). Results suggest that the model tended to be more reliable when the space heating was on. Minimum, average and maximum daily ventilation rates resulting from the application of the model to all homes when ΔT is over 5℃ are presented in Table 4.9.

Table 4.9: Representative figures for N.

Household	**Minimum**	**Average**	**Maximum**
H05	$> 0 \pm 0.9$	2.4 ± 0.4	9.8 ± 2.0
H08	$> 0 \pm 0.7$	1.0 ± 0.3	2.8 ± 2.7
H09	0.2 ± 1.3	1.9 ± 0.4	4.3 ± 0.8
H10	$> 0 \pm 0.9$	0.5 ± 0.3	1.2 ± 0.3
H18	$> 0 \pm 0.3$	0.9 ± 0.3	2.9 ± 2.8
H30	$> 0 \pm 0.5$	1.9 ± 0.6	7.1 ± 6.2
H37	$> 0 \pm 1$	2.1 ± 1.4	6.3 ± 3.4
H39	$> 0 \pm 0.8$	2 ± 0.6	7.4 ± 6.9
H41	0.1 ± 0.4	2.6 ± 1.2	11.2 ± 8.3
H43	0.1 ± 1.2	2.1 ± 1.0	7.2 ± 5.9
H46	$> 0 \pm 0.4$	0.6 ± 0.3	1.8 ± 1.5

The daily ventilation rate represents the heat exchange through infiltration and natural ventilation; average values vary within the sample between 0.5 Air Changes per Hour (ACH) and 2.6 ACH as shown in Table 4.9; average figures are within the range of those previous published values (Energy Saving Trust, 2014a; Bedford et al., 1943; Fabi et al., 2012). Low daily N rates mainly appear when ΔT is under 5℃ , as it is shown in Figure 4.2; but they also appear when ΔT is over 5℃ . Minimum values of N show greater uncertainty figures than the actual N values (see Table 4.9). Minimum N values are lower than expected, being in most cases below 0.1; the uncertainty of the calculation suggests that figures can be underestimated, being within the range of previous publications when taking consideration of the uncertainty.

Maximum values resulting from the model are within the range of those found in other studies, such as those suggesting ventilation rates between 3.1 and 3.2 ACH for multiple windows opened; or those from an empirical study which found N rates as high as 6.1 ACH when multiple windows were opened (Sheldon et al., 1989); and early work by Bedford reported ventilation air change rates as high as 30 ACH for cross-ventilated rooms in 6 London houses (Bedford et al., 1943).

Although there is high uncertainty in the modelling results, the output figures are within the range of those previously published. Maximum values are between those published in (Sheldon et al., 1989) and (Bedford et al., 1943); and, minimum values show lower rates than previous work but the uncertainty for those values demonstrate that the output figures are within those previously published.

Results suggest that the model can estimate reasonable N rates when the space heating is on, and by applying a ΔT threshold of 5℃ the model gives reasonable results. The use of the model is limited by its uncertainty and its lack of performance when ΔT is very low, usually during the summer season, but it has been demonstrated to have successful results when ΔT is over 5℃. The model can also be used by applying a threshold to the results uncertainty, in order to predict energy consumption. The purpose of the model in this study is to quantify whole house energy reductions from reducing the infiltration and the ventilation rate. The quantification only applies during the heating season as the ventilation rate will only impact energy consumption when the space heating is on.

The model is used in this thesis to estimate the N rate in the dwellings of study, and to estimate the potential energy reduction from reducing those values to minimum ventilation rates acceptable in domestic buildings as it is explained in the following chapter.

4.5 Summary

The parameters linked to behavioural attitudes and routines in the home are important to determine energy consumption in domestic dwellings (Hong et al., 2006). These need to be accounted for in energy reduction studies in order to generate values closer to the actual potential of energy demand reduction. The dearth of data has so far limited the modelling of energy consumption in dwellings, which are based on assumptions that strongly determine the use of energy for space heating, hot water and electricity supply. In this chapter an approach has been presented to estimate tailored energy consumption in a number of dwellings using monitored data. The results are evaluated to understand the viability of the approach by comparing the ventilation rate figures with previous findings, and by qualitatively validating the results from the model with householders' attitudes towards ventilation.

Results suggest that the application of the output household models developed here give plausible results, producing output ventilation rates similar to previous findings. The approach is limited by the simplifications made in the analysis and the number of uncertain parameters which are determined by applying assumptions and simplifications to the calculation. The uncertainty is especially high during the summer months, when the space heating is off and consequently the two components of ΔT approach each other. Temperature differences below 5℃ usually appear in the summer months when the space heating is off, suggesting that the model is more reliable if a ΔT threshold, in this case 5℃ is applied. This limitation is not especially relevant for the purpose of the model in this study, which is to calculate gas consumption for space heating purposes after applying reduction measures. Nevertheless, the approach should be further evaluated for different applications. Further work could also improve the resolution of the model, although the main issue for the increase of the resolution is that higher resolution should be approached with a dynamic modelling tool, which is difficult to balance with monitoring data, increasing the number of variables input into the equations and the approach uncertainty. Although the approach can be improved by a more detailed calculation method, it has demonstrated some value with respect to assessing household ventilation rates. The approach developed here achieves the Objective 3 set in Chapter 1 by characterising energy consumption and the ventilation rate in specific dwellings. The approach could be used to study tailored building energy consumption as smart meters enter the market and facilitate the collection of monitoring data; the whole modelling approach can be used to input measured data from energy consumption for space heating, indoor temperature, hot water and end use electricity in existing dwellings, to output daily ventilation rates without the use of standard coefficients, increasing the reliability from reduction analysis relating to ventilation parameters.

Chapter 5

Quantifying the impact of reduction measures

In this chapter, the whole house energy reduction assessment procedure is presented. The assessment quantifies energy reduction for a number of family homes, ranking the impact of each measure for each case study. A new action framework: REB, 'The Reduction Effort Balance', is developed as a concept to help visualise the balance between the potential of home retrofit and replacement investment and that from occupant behaviour change. A selection of measures has been modelled looking at their impact on space heating and electricity consumption. These impact on indoor temperature choice, space heating, building performance, end use appliance and ownership.

5.1 'REB' : Reduction Effort Balance

The literature review in Section 2.2, discusses reduction measures in the home and it is useful to place each of these in one of three categories. Energy reduction from:

- the retrofit of buildings;
- the replacement of appliances and systems; and,
- alternative measures which impact on users' convenience, choice and comfort.

The strategy from replacement and retrofit measures is different to that from lifestyle measures; replacement and retrofit need an investment whereas lifestyle measures need a reduction to service or a decrease in comfort. A distinction between technical and behavioural measures can therefore be made (Poortinga et al., 2003; Samuelson, 1990; Gardner and Stern, 1996).

The 'Reduction Effort Balance' quantifies the balance that exists between the potential role of lifestyle change, which historically has been given little emphasis in energy policy, compared with the impact from retrofit and replacement measures, which are the focus of most energy policy measures towards CO_2 targets in the domestic sector. The REB is informed by a review of retrofitting and demand reduction studies, combined with the practical results gained in this work.

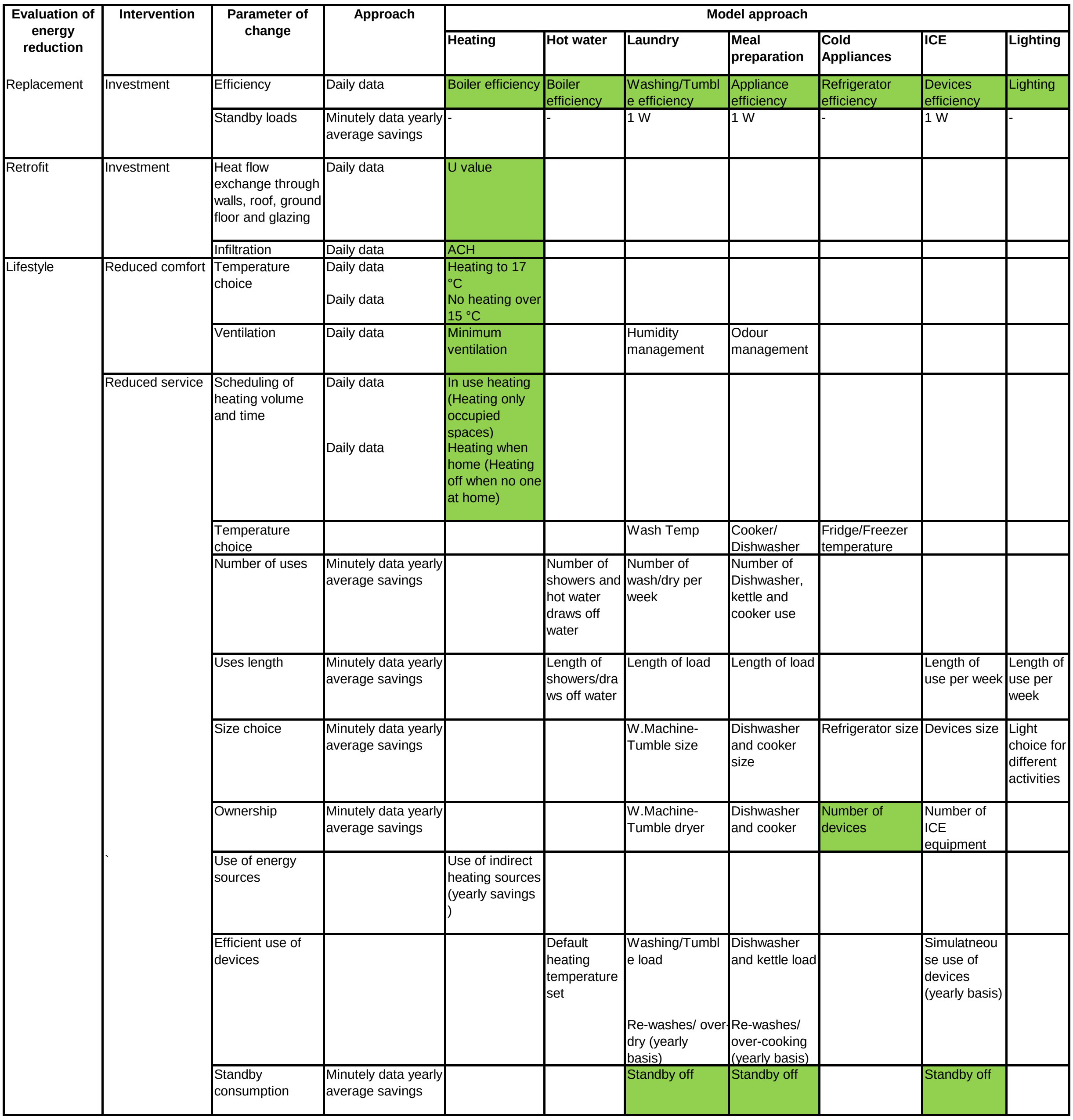
Lifestyle: these do not necessarily cost anything, but require the user to accept a different level of convenience, choice (defined together here as service) or comfort than they are used to;

Replacement: items that require small to moderate investment, but are not particularly disruptive to carry out, such as replacing an old appliance; and,

Retrofit: major undertakings that usually affect the building fabric or heat production (i.e. the boiler) that are a significant cost and undertaking.

In this work, the modelled measures have been selected from an exhaustive literature review of the potential energy demand reduction measures in domestic buildings; possible energy demand reduction measures are summarised in Table 5.1. The selection criteria followed to underpin the reduction measures finally applied was:

- the reduction measures' impact on gas, hot water and electricity energy demand;
- the reduction measure entails an improvement on the efficiency of the appliance or system;
- they reduce the energy consumption by reducing the service supplied, either decreasing wasted energy or users' comfort levels;
- the measure impact can be tailored to the household by applying the monitoring data; and,
- the assumptions needed for the analysis do not imply current usage efficiency that can not be determined (for example if the washing machine is fully loaded).



Evaluation of energy reduction	Intervention	Parameter of change	Approach	Model approach						
				Heating	**Hot water**	**Laundry**	**Meal preparation**	**Cold Appliances**	**ICE**	**Lighting**
Replacement	Investment	Efficiency	Daily data	Boiler efficiency	Boiler efficiency	Washing/Tumble efficiency	Appliance efficiency	Refrigerator efficiency	Devices efficiency	Lighting
		Standby loads	Minutely data yearly average savings	-	-	1 W	1 W	-	1 W	-
Retrofit	Investment	Heat flow exchange through walls, roof, ground floor and glazing	Daily data	U value						
		Infiltration	Daily data	ACH						
Lifestyle	Reduced comfort	Temperature choice	Daily data Daily data	Heating to 17 °C No heating over 15 °C						
		Ventilation	Daily data	Minimum ventilation		Humidity management	Odour management			
	Reduced service	Scheduling of heating volume and time	Daily data Daily data	In use heating (Heating only occupied spaces) Heating when home (Heating off when no one at home)						
		Temperature choice				Wash Temp	Cooker/ Dishwasher	Fridge/Freezer temperature		
		Number of uses	Minutely data yearly average savings		Number of showers and hot water draws off water	Number of wash/dry per week	Number of Dishwasher, kettle and cooker use			
		Uses length	Minutely data yearly average savings		Length of showers/draws off water	Length of load	Length of load		Length of use per week	Length of use per week
		Size choice	Minutely data yearly average savings			W.Machine-Tumble size	Dishwasher and cooker size	Refrigerator size	Devices size	Light choice for different activities
		Ownership	Minutely data yearly average savings			W.Machine-Tumble dryer	Dishwasher and cooker	Number of devices	Number of ICE equipment	
	`	Use of energy sources		Use of indirect heating sources (yearly savings)						
		Efficient use of devices			Default heating temperature set	Washing/Tumble load Re-washes/ over-dry (yearly basis)	Dishwasher and kettle load Re-washes/ over-cooking (yearly basis)		Simulatneouse use of devices (yearly basis)	
		Standby consumption	Minutely data yearly average savings			Standby off	Standby off		Standby off	

Figure 5.1: Classification of reduction measures and highlight of selected measures for the analysis with the modelling approach summarised.

These are summarised and classified in Figure 5.1, differentiating between consumption categories: heating, hot water, laundry, cooking, cold appliances, ICE[1] technologies and lighting (Coleman et al., 2012). After application of the selection criteria, the measures highlighted in green in Table 5.1 were chosen and applied. Reductions that entailed a lower level of service but that required applying assumptions on the 'most efficient' use of appliances and lights were rejected due to the considerations needed in order to model them, which would need subjective reflections about family needs and the efficiency of practices. For example, measures such as reducing the length of the oven time, reducing the number of wash loads or the washing temperature were not modelled, even though the application of those would eventually reduce energy consumption by changing householders' lifestyle; further measures were not evaluated due to monitoring data constraints, such as the analysis of potential reductions from having showers instead of baths.

Table 5.1: Energy reduction measures at a glance.

Type	**Affects**	**Measure**
Lifestyle	Service reduction	One fridge-freezer
		No standby loads
		No tumble drying
		Heating when home
		In use heating
	Reduced comfort	No heating over 15℃
		Heating to 17℃
		Ventilation
Replacement	Cooking appliances	New appliances
	Cold appliances	New fridge-freezer
	Laundry appliances	New laundry appliances
	Digital media devices	New media equipment
	Doors	Insulated doors
	Lighting	Replace bulbs
Retrofit	Loft	Loft insulation
	Walls	Wall insulation
	Floor	Floor insulation
	Windows	Triple glazing
	All building	Sealing
	Heating system	New boiler

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[1] ICE: Information, communication and entertainment

5.2 Space heating energy reduction

Space heating consumption can be reduced through the implementation of better technologies and materials by: increasing fabric insulation, increasing house airtightness, applying mechanical ventilation and increasing the boiler heating efficiency. Changes in comfort and service that yield a reduction in space heating demand are delivered by decreasing the comfort levels of users in relation to levels of temperature, humidity and fresh air levels in the indoors. The limitation of comfort and service measures have been studied by decreasing the indoor temperature during heating times, reducing the total heated volume in the house, reducing the space heating when the house is empty, and by reducing seasonal heating. The effects on space heating that have been treated in this study are given below:

1. 'Heating when home': using space heating only when the house is occupied, by applying three different occupancy patterns based on householder reported schedules.
2. 'In use heating': ensuring the heating is off at night when the family is sleeping; and, that only occupied spaces are heated, for example when there is only one person working from home, heating only the studio or the living room.
3. 'No heating over 15 ℃' : minimising the seasonal use of space heating by ensuring the system switching off when the outdoor temperature is over 15 ℃.
4. 'Heating to 17℃': lowering the indoor temperature set point so the maximum peak temperature is 17 ℃.
5. 'Ventilation' : minimising the air change rate within the building.
6. 'Sealing' : Reducing the infiltration rate to minimum values after modelling sealing measures.
7. 'Retrofit': Reducing the U-values from building elements to best standards.

5.2.1 Heating when home

In this analysis there are assumptions made as to when householders are at home and when the heating could be switched off with no direct impact on the user comfort but only the level of service required. The assumptions are based on participants reported weekly occupancy.

During weekend days the whole house is assumed to be occupied and so the existing settings are applied. The average temperature over the day was modelled based on the hourly occupancy profile presented in 3.3.5, which varies depending on the working day schedule. A default temperature of 16℃ is applied to the model for unoccupied periods of time and current monitored temperature is applied to occupied hours. The minimum temperature of 16℃ is set in the model to guarantee that gas requirements for a minimum adequate indoor temperature are supplied, given that below this temperature the building fabric and its contents, such as service pipes and other indoor elements can be unprotected from condensation and/or frost (The Chartered Institution of Building Services Engineers, London, 2005).

The model recalculates the average indoor temperature over the day once applied the time and temperature conditions to set the new differential of temperature to the heat balance equation and calculate the ventilation heat exchange, Qv_{off}, based on the current air change rate; fabric heat loss calculation, Qf_{off} is then the output from the model.

$$Q_{g_{off}} = Qv_{off} - Qp - Qe + Qf_{off} + Qw_{loss} - Q_{water} - Qs \tag{5.1}$$

5.2.2 In use heating

This energy reduction measure evaluates the impact of controlling the temperatures in rooms based on their use and occupancy. The assumption is that rooms are unoccupied but heated as households are centrally heated; these rooms can be kept at lower temperatures, or even not heated at all during unoccupied periods.

This analysis considers how much energy could be saved if users were to heat the whole house for only one hour in the morning, the living room for the whole evening as usual and to heat only one specific room if someone is at home during the day. The temperatures in the ‘unused’ rooms are maintained to at least 16℃. The analysis is based on the family occupancy profile, which identifies three different day schedules based on reported family timetables: working days, working from home days and weekend days. Working from home and weekend days have different schedules due to the difference in occupancy during the day. For working from home days the assumption is that the studio/living room is the working space and therefore, the only space heated during the day, supplying heat to the person working from home; during the evenings the assumption is that only the living room is heated, which is assumed to be the family space. Unoccupied spaces will cool down when they are not heated, as the space is not in use; the model considers the amount of gas needed to keep those rooms at a minimum temperature of 16℃.

The hourly schedule applied in the analysis is as follows: for assumed sleeping hours (from midnight to 7.00 a.m.) the modelled temperature is set at 16℃ in the whole house; for morning waking hours (from 8.00 a.m. to 9.00 a.m.) current monitored temperature is maintained; for working hours, which vary with working schedules, the default temperature is applied; and for evening hours, which again, depend on working hours, the default temperature is applied in the whole house but in the assumed occupied space, the living room, which is heated to actual monitored temperature.

Ventilation heat loss and fabric conduction, $Q_{g_{in}}$, and $Q_{v_{in}}$, are recalculated once the schedule is applied to the temperature data, using the output daily calculation from the model.

$$Q_{g_{in}} = Qv_{in} - Qp - Qe + Qf_{in} + Qw_{loss} - Q_{water} - Qs \tag{5.2}$$

5.2.3 No heating over 15 ℃

The duration of the heating season impacts on annual energy consumption. The seasonal turning on and off of the heating has therefore an important potential for energy reduction; currently, the time to turn on and off the heating strongly depends on user preferences and outside air temperature. To minimise the duration of the heating time, the impact of slightly lower temperature indoors during the middle seasons is evaluated; the model applied switches off the heating when the average outdoor temperature over the day is over 15 ℃, recalculating the energy required to satisfy the new schedule.

Equation 5.3 was applied in the model for daily temperature figures over 15℃, and Equation 5.4 was applied for outdoor temperature over 15℃

$$Q_{sh_{15}} = 0 \tag{5.3}$$

$$Q_{sh_{15}} = Q_{sh} \tag{5.4}$$

Figure 5.2 shows the monitored daily gas consumption in blue and the models daily gas consumption prediction output in red; as it can be seen in the graph, the model only recalculates the gas consumption over the summer months, from April to October, whereas during the rest of the year, the consumption remains constant (hence the blue points are under the red ones).

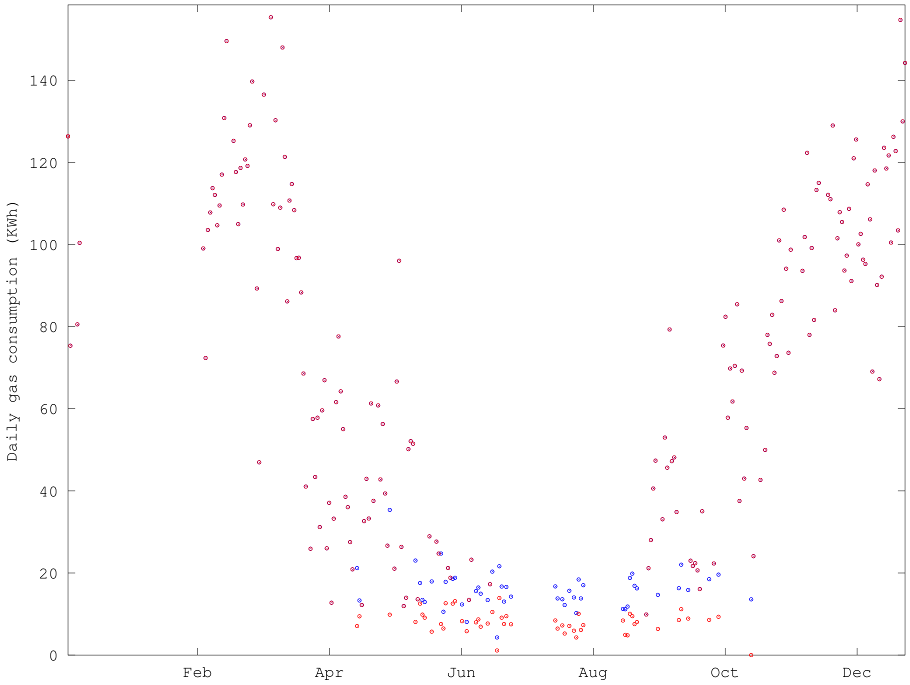

Figure 5.2: H30 daily gas consumption before (blue) and after (red) applying the model 'No heating over 15 ℃'.

5.2.4 Heating to 17 ℃

The 17℃ setting is slightly lower than the minimum indoor temperature suggested in some studies which evaluate minimum health standards in occupied rooms. Temperature considerations vary with the occupant activity level and age, with values ranging between 18℃ and 21℃ (Wookey et al., 2014). Although this is the suggestion from studies looking at minimum health standards, UK scenarios evaluating the transition to a low carbon energy system suggest a peak indoor temperature of 17℃ in domestic dwellings (UK Energy Research Centre, 2009) as temperature settings are strongly linked to energy consumption. The analysis considers 17℃ as the minimum threshold and this assumption is discussed with householders in the second stage of the study, to understand the credibility of this assumption and to evaluate what would be their lowest temperature choice. Householders' insights on this measure are especially relevant, as the reduction of peak temperature to 17℃ would heavily impact on householders' thermal comfort, being significantly lower than current peak indoor temperature as can be seen in Table 3.7, Chapter 3.

The reduction achieved by lowering the indoor temperature is evaluated by estimating the volume of gas needed to reach the new temperature. A condition is added to the equation to model gas consumption only when the space heating is on based on household monitoring data. The model evaluates hourly indoor temperature and applies the new condition, recalculating the new daily temperature figure. The latter is implemented thus, where $Q_{f_{17}} + Q_{v_{17}}$ are the fabric and ventilation losses at the new lower temperature and Q_e, Q_p, Q_s, Q_w and $Q_{w_{loss}}$ are the estimates from the data. The expression then is a function of temperature difference.

$$Q_{sh_{17}} = Q_{w_{loss}} + Q_{f_{17}} + Q_{v_{17}} - (Q_e + Q_p + Q_s + Q_w) \tag{5.5}$$

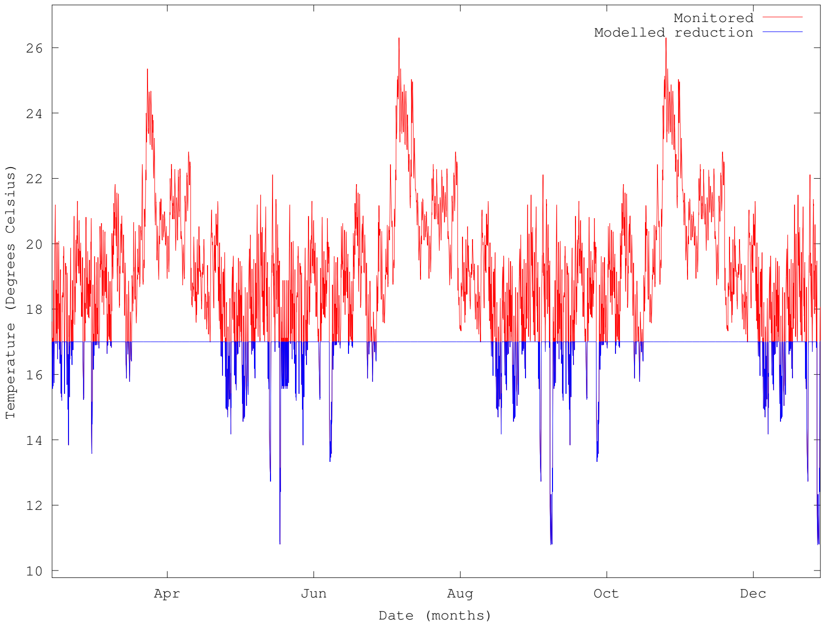

Figure 5.3: Monitored and modelled daily indoor temperature figures in H05.

A graphical example of the reduction measure implication is shown in Figure 5.3, which shows the daily indoor temperature calculated based on the available monitoring sensors and the temperature resulting from the reduction model in H05.

5.2.5 Ventilation

Ventilating in the heating season does have an energy penalty. In the analysis, a hypothetical scenario was selected where householders only ventilate the home to the minimum level required to satisfy the physiological needs of the occupants, which is probably much lower than householders typically feel comfortable with. This extreme case is unobtainable in reality, at least without a mechanical ventilation system, but it acts as a constraint that defines the lowest possible ventilation rate and hence the greatest possible reduction.

The reduction achieved by decreasing the air change rate is evaluated by estimating the volume of gas needed to reach current monitored temperature with the new heat loss estimation. The latter is implemented thus,

$$Q_{sh_{new}} = Q_{w_{loss}} + Q_{f_{new}} + Q_{v_{new}} - (Q_e + Q_p + Q_s + Q_w) \tag{5.6}$$

where $Q_{f_{new}} + Q_{v_{new}}$ are the fabric and ventilation losses at the new lower ventilation rate and Q_e, Q_p, Q_s, Q_w and $Q_{w_{loss}}$ are the estimates from the data.

The results from applying Equation 5.6 are subjected to a condition in order to meet the minimum health requirement for air change rates in dwellings, which is applied in the ventilation measure; this minimum figure is assumed from Building Regulations and previous work on health fresh air standards (Office of the Deputy Prime Minister, 2010). The most restrictive figure from applying Building Regulation figures based on the size of the building and those from applying the minimum ventilation rate to satisfy the supply of fresh air in the number of rooms, is modelled (Office of the Deputy Prime Minister, 2010). If the infiltration value obtained after modelling sealing measures, is lower than the minimum health standard $vent_{min}$ or $vent_{min2}$, then the upper limit for the minimum health standard is applied in the model. The coefficient $vent_{min}$ is calculated for a standard British 3 bedroom dwelling, and $vent_{min2}$ is calculated considering the dwelling floor area:

$$vent_{min} = 0.029 + (0.004 \times 3) \tag{5.7}$$

$$vent_{min2} = 0.0003 \cdot m^2; \tag{5.8}$$

The upper graph in Figure 5.4 shows the daily figures of the ventilation heat loss resulting from applying the heat balance principles to the monitored data (blue dots) and the ventilation heat loss achieved after applying the ACR reduction (red dots). The lower graph shows the impact of the ventilation heat loss on the space heating consumption. Blue dots represent the daily values from monitored space heating consumption and red dots the reduced space heating consumption for the reduced ventilation heat loss modelled in the analysis.

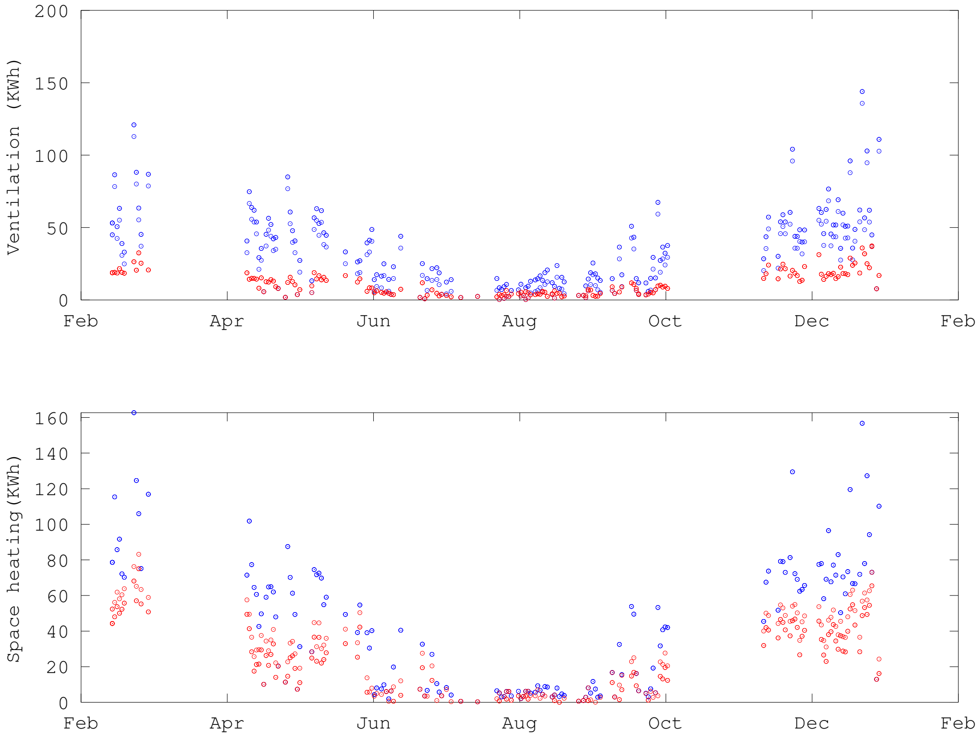

Figure 5.4: H05 Space heating (below) and ventilation heat loss (above) before (blue) and after (red) modelling the ventilation measure.

5.2.6 Sealing

Infiltration is the uncontrolled exchange of air between the inside and the outside of a building, which takes place through cracks in the building fabric, doors, glazing, existing mechanical and electric fans, flues and chimneys; this is caused by pressure difference, effects of the wind and/or the stack effect.

The evaluation of the infiltration rate in a dwelling can be either monitored or modelled by assuming a number of building element characteristics. The monitoring of the infiltration rate can be performed by a pressure test to determine the airtightness of the house. Most commonly, existing models estimate the infiltration effect by attributing air leakage to the building elements. In this study, the BREDEM approach has been used in order to estimate the infiltration of the dwellings before and after applying sealing measures. BREDEM values for infiltration rates from the building fabric and other building elements which affect ventilation are assumed in the model based on the building characteristics summarised in Table 5.2. BREDEM values assumed in the calculation are detailed in Tables B.1,B.2,B.3 and B.4 in Appendix C.

Table 5.2: Variables considered in the infiltration calculation.

Description	**Parameter**	**Type**	**Units**
Dwelling infiltration	Inf	Calculated	h^{-1}
Building elements infiltration	N_{be}	Calculated	m^3 / h
Chimney infiltration	N_v	Constant	h^{-1}
Structural elements infiltration	I	Calculated	h^{-1}
Sheltered factor	S_h	Constant	-
Dwelling exposure factor	D_h	Constant	-
Dwelling Volume	V_dw	Measured	m^3
Temperature difference	ΔT	Calculated	degc
Conversion rate from Watts to MJ	WMJ	Calculated	-
Heat loss through infiltration	Q_{inf}	Calculated	MJ
Wind speed	w	Monitored	m/s

Published infiltration rates from a case study by Hall et al. that demonstrates the impact of sealing are used to analyse the potential reduction for the sample of houses (Hall et al., 2013).

The following building characteristics are taken into account for the evaluation of current and potential infiltration:

- site exposure factor,

- dwelling exposure factor,
- wind speed,
- ΔT

where,

$$Inf = (N_{be} + I)S_h \cdot D_h \frac{w}{4} \tag{5.9}$$

$$N_{be} = \frac{N_v}{V_{dw}} \tag{5.10}$$

$$Q_{inf} = \frac{Inf \cdot V_{dw} \cdot \Delta T \cdot WMJ}{3}; \tag{5.11}$$

$$WMJ = \frac{60 \times 60 \times 24}{1000000}; \tag{5.12}$$

A new infiltration rate, $Q_{inf_{new}}$, is then applied as in Equation 5.13 to the model based on the potential infiltration after applying sealing, draught proofing and installing a MVS [2]. The infiltration value applied in the model is based on the results of Hall et al.'s study, which reported air changes per hour down to 0.41 on an existing Midlands semi-detached house (Hall et al., 2013) after draught-proofing service risers, pipe work envelope penetrations (radiators, water pipes etc.) and boiler flues, covers fitted to door locks, kitchen fan removed and sealed with the insulated under-croft and the installation of a MVHR system. If the output ventilation rates are lower than minimum ventilation rates to meet health requirements, health standards are applied.

$$Q_{v_{new}} = Q_v + Q_{inf_{new}} - Q_{inf} \tag{5.13}$$

The results from applying Equation 5.13 are shown in Figure 5.5; the graph above shows the ventilation heat loss before (blue) and after(red) applying the sealing measure to the model and the graph below shows the output ventilation rate.

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[2] MVS: Mechanical ventilation system

Figure 5.5: H05 Modelled ventilation output before (blue) and after (red) modelling the effect of sealing the house on ventilation heat loss (above) and on the estimated ventilation rate (below).

5.2.7 Improved insulation

The space heating reduction from retrofitting was modelled by applying the best standard U-values that are expected in the UK regulations, considering the most stringent values to determine the highest possible reduction. U-values are those from The Scottish Building Standards for dwellings with minimal insulation, which are the most restrictive. The values considered in the Scottish Building Standards are very close to those suggested in the 'Stock Take' report, which was previously published by The Sustainable Development Commission to make energy performance recommendations to existing homes, (Commission of Sustainable Development, 2006). The values applied in the calculation are summarised in Table 5.3.

Table 5.3: Retrofit U-values for building elements applied in the model.

Element	**Construction**	**U-value ($\mathbf{W/m^2K}$)**
Windows		1.4
Roof	Pitched	0.13
Floor	Any exposed floor	0.15
Walls	All	0.19
Doors	Glassed	1.5
	Solid	1

The fabric heat loss, $Q_{sh_{new}}$, after the application of reduced U-values was calculated as in Equation 5.14.

$$Q_{sh_{new}} = Q_{w_{loss}} + Q_{f_{new}} + Qv - (Q_e + Q_p + Q_s + Q_w) \tag{5.14}$$

Doors

Doors are a source of heat loss and infiltration, and the impact on energy consumption from replacing the door with one that is highly air tight and which has top level insulation is modelled. Reductions are estimated by comparison between current heat loss, and heat loss from best standard doors in the literature.

Loft

There are plenty of possibilities for insulating the loft, even though these are limited by the characteristics of the loft and its use and accessibility. The roof insulation materials are often the same as for wall insulation. Increasing the loft insulation to the highest standard, i.e. 300mm rockwool or equivalent, will reduce the heat loss through the upstairs ceiling. The analysis estimates the reduction from changing current materials to the highest standard found in the literature.

Walls

Solid brick walls have a high energy reduction potential as discussed in previous studies. External wall insulation can be fixed to the wall and covered by rendering or cladding, which is then finished by painting, tiling, panelling, pebble-dashing or adding brick slips. In addition, internal wall insulation can be installed by adding a stud wall filled in with insulation or by fitting insulation rigid boards in the internal surface (Energy Saving Trust, 2014b). The insulation from cavity walls can also be improved, either by adding insulation to the cavity and/or adding insulating solutions to any of the surfaces as for solid brick walls. Cavity wall insulation is usually carried out by using mineral wool materials, either rock or glass mineral wool, but there are other advanced materials based on expanded polystyrene beads or granules, using urea-formaldehyde foam (Energy Saving Trust, 2002).

In this analysis, top level U-values are considered regardless of the wall type, as both solid wall and cavity walls can achieve these minimum standards. The viability of applying this measure varies with the cost of the retrofit together with the reduction expected from it, being unlikely to take place in households where the difference in the insulation levels is not cost-effective, such as insulated cavity wall dwellings.

Floor

The retrofit of the ground floor to achieve best insulation standards requires the replacement of the screed for solid floors or insulation fitting between floor joists prior to replacement of the floor deck (HM Government, 2010). There are other options that can improve the thermal characteristics of the floor such as adding rugs and carpets, which improves user thermal comfort and blocks any existing draughts.

The model applies the standard ground floor typology and the insulation levels mandatory at the year of construction. The reduction measure evaluates the impact of applying best insulation solutions, which could be achieved either by removing a layer from the solid floor and adding an insulating floor decking or taking up the wooden floor and adding insulation between the floor joists.

Windows

The glazing heat transmittance has improved considerably in the past years due to new insulating techniques and materials for double glazing, triple glazing and in the worst case scenario from the addition of secondary glazing. There are ‘ecolabels’ and standards for windows such as the Nordic Swan, New Zealand, Canada and Australian energy rating ecolabels, the Korean Ecolabel, the Taiwan GreenMark, the UK Energy Saving Recommended Logo and the US and

Canadian Energy Star systems. Different ecolabels have varying scope, and they are influenced by the regional climate and by the dwelling characteristics, rather than following a generic set of criteria. Many of these ecolabels are only examples of best practice and represent good quality work and performance (DG Environment, 2010). The investment on high standard triple glazing has an impact on energy consumption, which depends on the glazing surface and on current glazing characteristics. The analysis considers a standard U value for single and double glazing and estimates a proxy energy reduction from installing triple glazing, based on published U-values from triple glazed windows.

5.2.8 New boiler

The efficiency of the boiler and how it operates is an important factor for energy consumption. In this analysis, the efficiency of the current boilers has been assumed and compared to that of the best quoted efficiency of a new boiler. The efficiency rate expected for 2050 commercial boilers is assumed at 95% (Boardman et al., 2005); the current boiler efficiencies are assumed from the specifications at the SEDBUK seasonal database for each boiler model (SEDBUK, 2014). One of the limitations of this evaluation is that in reality, the operational efficiency of condensing boilers is different to that given by SEDBUK and it depends on a number of variables such as boiler settings and radiators size in the case of space heating and draw off characteristics for hot water usage.

$$Vg_{new_{boiler}} = \frac{Q_g}{Cv_{gas}\epsilon_{new}} \tag{5.15}$$

5.3 Electricity reduction

The energy reduction from acquiring new appliances with improved efficiency is analysed by considering a standard increase in the efficiency rate for monitored devices (ϵ). Where there is a reduction on an appliance, i.e. a fridge is replaced with a more efficient one, then this is applied to the specific device and so the loads are disaggregated. Reductions have been carried out for the end use monitored electrical loads and classified according to the DEFRA categories with the exception of computer and audio-visual equipment, which in this study is considered as ICE equipment (Coleman et al., 2012); and cleaning equipment, which in this case is not differentiated from ‘other equipment’. Cold appliances include all refrigerators;

lighting is measured in the lighting circuits and in some of the lights individually monitored; audio-visual equipment and computers are included in the ICE category and account for TVs, audio-visual devices, mobile phones and routers; cooking appliances include all the electric monitored devices used for heating and/or processing food; and clothes washing, and drying appliances are classified as laundry equipment. Electric loads which do not fall neatly into these categories are accounted for as 'others' and unmeasured power is deduced from the mains power supply and categorised here as 'unknown'. The main limitations of the electric demand reduction analysis are:

- monitored devices are not consistent in the sample, so results are difficult to compare, i.e in a sample house there are two TVs but only one is monitored, whereas in another house all TVs are monitored; and,
- the number of controlled devices in a category do not always account for all the devices used in the house, so the results do not give a complete picture of the electric demand but only an approximation of the possible reductions for a given category based on monitored devices.

The proportion of measured appliances grouped within the categories is listed in Table 5.4; monitored appliances range from 40% in H43 to 85% in H05; categories captured between 42% and 91% of the electric energy use. Previous studies looking at inferable electrical data were able to report similar proportion of loads, with up to 46% of non inferable loads (Stankovic et al., 2015). The assessment of reduction measures is limited by this issue, as reductions would be higher in houses where the percentage of known loads is higher. In order to deal with this limitation, the approach has been to assume that the distribution of 'unknown' loads follows the same proportion as that from monitored loads, assigning a percentage of 'unknown' electricity loads to each category, with the exception of the laundry category as laundry appliances were fully monitored within the sample. An example of the approach is given for ilustration, if cooking accounts for 20% of the energy consumption in one household and 'unknown' loads are 30% of the total, 6% of 'unknown loads' is added to the cooking category, which accounts for 36% of the electricity consumption.

Table 5.4: Monitored appliances within categories.

Category	**H05**	**H09**	**H10**	**H30**	**H37**	**H39**	**H46**
Laundry	2	2	2	2	2	1	2
Cooking	6	5	5	5	5	3	4
Cold appliances	2	3	2	1	2	2	1
Computer equipment	4	3	5	5	3	5	3
Audio-visual	3	4	1	1	2	2	7
Dish washing	0	0	0	1	1	1	1
Hot water heating	0	1	0	0	1	1	0
Lighting (circuits/lamps)	4	6	5	8	8	3	2
Other devices	8	5	3	2	5	3	4
Total monitored	29	29	23	25	29	21	24
Appliances ownership	34	36	39	33	37	42	49
Monitored %	85.29	80.55	58.97	75.76	78.38	50	48.98
Electricity %	42.32	75.15	50.74	91.09	52.75	79.81	83.39

5.3.1 One fridge-freezer

The impact of owning a single fridge-freezer is studied here as part of the potential lifestyle change that would impact on user service. This reduction is applied to all households but H46, which only owns one fridge-freezer as shown in Table 5.5 and H30, whose second fridge freezer was not monitored. Reductions were modelled by recalculating energy consumption after discounting any second and third refrigerator from the electricity supplied as in Equation 5.16.

Table 5.5: Refrigerators ownership sample.

Variable	**H05**	**H09**	**H10**	**H30**	**H37**	**H39**	**H46**
Refrigerators ownership	2	3	2	2	2	2	1

$$Qe_{cold_{min}} = (Qe_{cold} - Qe_{fridge}) \tag{5.16}$$

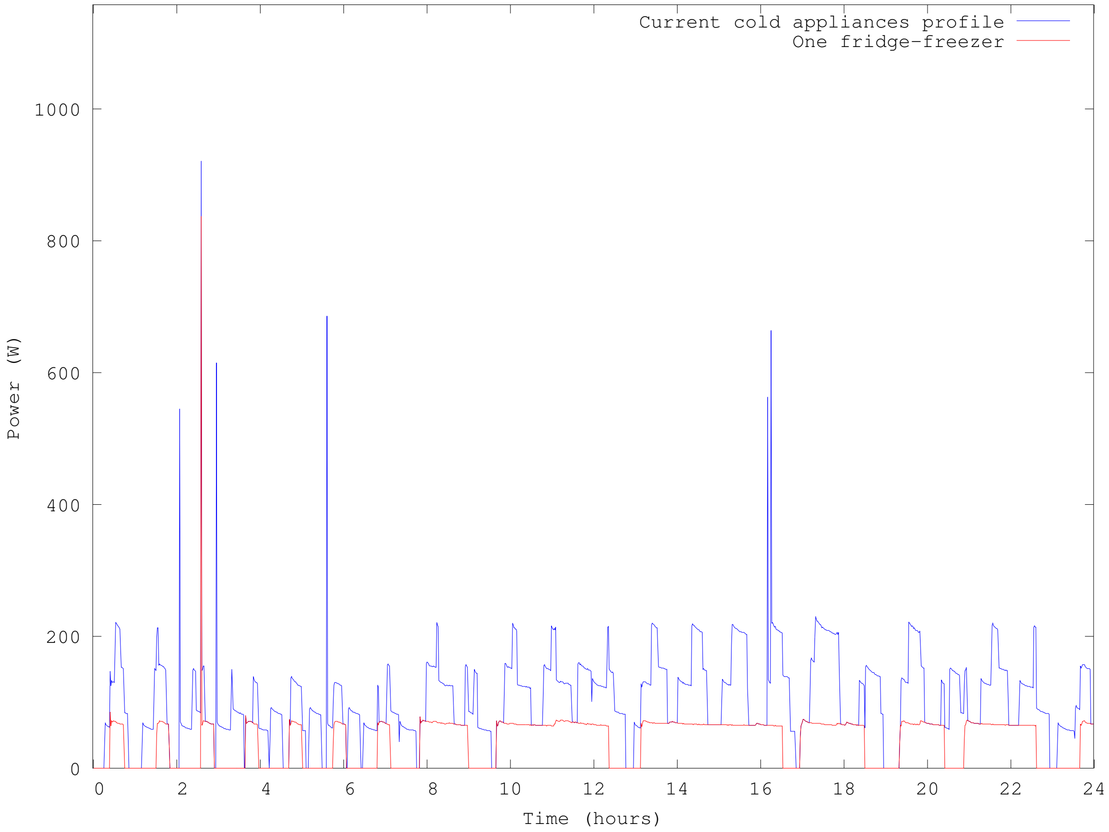

Figure 5.6: H09 sample day power profile from cold appliances.

5.3.2 No standby loads

Standby loads appear when specific appliances are not in use but are connected to the switch. These can consume energy that is overlooked by most users (Coleman et al., 2012), particularly in older appliances. Standby loads can be either switched off manually, which will impact on how people use the devices, or switched off automatically, enabled by smart home controls. The standby potential reduction was modelled by using minute samples, as the analysis includes modes of operation that are time dependant during the day. A TV, for example, might have a standby load and so a time series model is applied to evaluate the reduction generated by switching it off when not in use. This is calculated as in Equation 5.17 based on the standby loads found in the data and summarised in Table 5.6.

Table 5.6: H05 standby loads identified in monitored devices.

Device	**Sample standby loads (W)**
TV in bedroom	4
Computer equipment extension	17
Tumble drier	1
iPad charger	1
Washing machine	1
Cooker	1
TV in living room	7
iPad dock/Laptop	1

$$Q_{newstandby} = Q_e - Q_{standby} \tag{5.17}$$

5.3.3 No tumble drying

Tumble dryer loads can be significant in households that use them on a regular basis to dry clothes. The model quantifies how much energy could be reduced by changing current laundry routines, from using the tumble dryer to hanging out washing. Figure 5.7 shows the power consumption from the washing machine and the tumble dryer during a sample week in H46, which is the household that most frequently uses the tumble dryer from the sample. The graph shows in blue their current consumption, where the washing machine load and that from the tumble dryer can be identified; the red line shows the power profile after eliminating the tumble dryer use.

The model quantifies the new electricity consumption $Qe_{laundry_{min}}$ by deducing the tumble dryer loads from the laundry loads as shown in Equation 5.18:

$$Qe_{laundry_{min}} = (Qe_{laundry} - Qe_{dryer}) \tag{5.18}$$

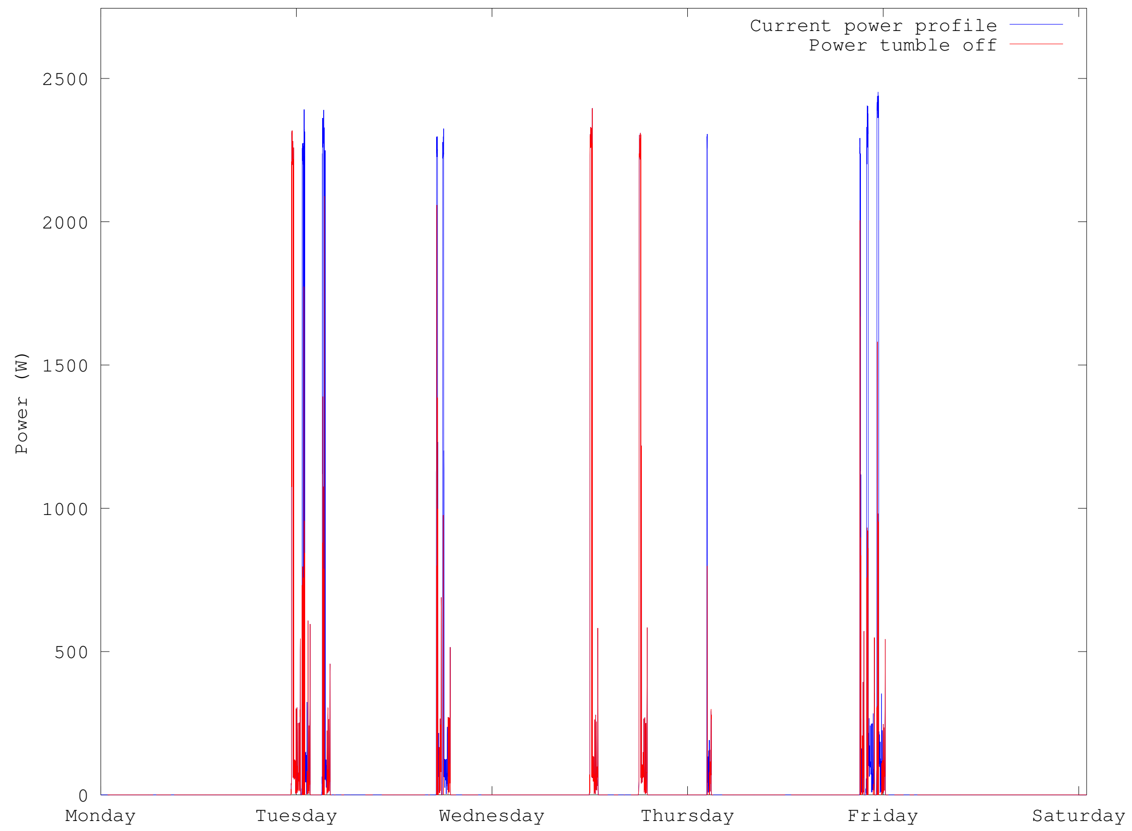

Figure 5.7: H46 power profile with and without the use of the tumble dryer.

5.3.4 Bulb replacement

The replacement of incandescent lights by LEDs is analysed by applying a percentage of current inefficient lights in the home, the percentage of which were self reported at the beginning of the project. The analysis considers an 80% reduction from old bulbs to new LEDs, modelling the new electricity input after applying the reduction to the lights power.

5.3.5 Appliance replacement

The appliance market is continuously reaching higher efficiencies. The energy rating of appliances is aimed to promote companies interest in increasing energy efficiency by informing clients on the relative energy efficiency of the devices. The improvement grades these efficiencies will reach in the future depends on the technology developments and the current technology in place. For this analysis, we consider technologies that are either already available or could be expected in the next 10 years. The following forecast is used as a simplification of the reductions that can be expected in the future, assuming a conservative efficiency increase of 1% per year (Department of Energy & Climate Change, 2010) and 10 years for the lifespan of domestic appliances (Weiss et al., 2010), with the exception of gas ranges, which are expected to have a longer lifespan (15 years) (Seiders et al., 2007).

The estimation of potential reductions from new appliances can be re-evaluated as efficiency change, by updating new devices efficiency rate; this is a flexible approach that can be customised to re-calculate specific electrical reductions for specific appliances.

5.4 Energy reduction potential

The model estimates the overall whole house reduction by simultaneously applying all reduction variables, recalculating the gas, $Q_{gas_{min}}$, and the electric consumption, Qe_{min} to estimate whole house energy consumption.

5.4.1 Electricity consumption

The minimum electricity demand Qe_{min} is that from applying the reduction coefficients to monitored appliances and lighting, reducing the electricity consumption from any second and third refrigerator, the tumble dryer and the power load from standby loads. The calculation formula is the following:

$$Qe_{min} = Qe_{cold_{min}} + Qe_{laundry_{min}} + Qe_{ICE_{min}} + Qe_{cooking_{min}} + Qe_{lights_{min}} + Qe_{other_{min}} + Qe_{dif} - Q_{standby} \tag{5.19}$$

5.4.2 Gas consumption

The minimum gas consumption after the application of all reduction measures, $Q_{gas_{min}}$, is modelled by applying the following parameters: minimum Air Changes per Hour (ACH), infiltration rate after sealing intervention, maximum peak temperature of 17 ℃, heating time adjusted to occupancy, heating volume adjusted to occupied rooms, new boiler efficiency, and Qe_{min} input.

$Q_{gas_{min}}$ is given by Equation 5.20 and the parameters involved in the estimation are listed in Table 5.7.

Table 5.7: Parameters involved in the calculation of the minimum gas consumption.

Description	**Parameter**	**Units**
Minimum gas demand	$Q_{gas_{min}}$	MJ
Minimum ventilation output	Qv_{min}	MJ
Minimum fabric heat loss	Qf_{min}	MJ
Minimum ventilation rate	$vent_{ratemin}$	ACH
Minimum temperature difference	ΔT_{min}	℃
U values from retrofitted elements	U_{min}	MJ/m^2C

$$Q_{gas_{min}} = Qv_{min} + Q_{w_{use}} - Q_{e_{min}} - Q_p - Q_s + Q_{w_{loss}} + Qf_{min}, \tag{5.20}$$

where,

$$Qv_{min} = \frac{vent_{ratemin} \cdot Vhouse \cdot \Delta T_{min}}{3} \tag{5.21}$$

$$Qf_{min} = \sum U_{min} \cdot \Delta T_{min}. \tag{5.22}$$

The minimum ventilation rate, '$vent_{rate}min$', is the ventilation rate which meets the following specifications: it is the highest value between the minimum fresh air specifications and the lowest infiltration rate achievable after applying sealing measures.

The daily indoor temperature ΔT is calculated after applying to the hourly schedule the following specifications:

- for occupied periods of time during working days the temperature is set at 17℃ for inhabited rooms, for unoccupied rooms the temperature is defaulted to 16 ℃; and,
- for weekends, indoor temperature stays as it is for data points where the temperature is lower than 17 ℃, and is reduced to 17℃ otherwise; no further assumptions are applied relating to which spaces are occupied.

5.4.3 Quantifying the REB

The same approach applies for the quantification of REB, which is evaluated by setting two scenarios: the first only considers lifestyle measures and the second only applies replacement and retrofit measures to the model.

5.4.4 Annual energy calculation

The daily data analysed over 2013 does not fully represent the annual consumption, as data missing for days or specific periods of time can misrepresent part of the year. Data was pre-processed and treated before the analysis was performed, as explained in Chapter 3, in order to normalize the data before calculating the annual figure. Annual results are then evaluated in order to analyse the impact of reduction measures upon family homes energy consumption.

5.5 Contextualisation of energy reductions

The model results were contextualised with 2050 targets in order to discuss with householders how far they were from achieving 2050 targets. The argument is that if there is a national 2050 target energy consumption, there is a 'sustainable' level of energy consumption to aim for; then, the role of this figure is to frame the analysis, setting an hypothetical target that householders can easily understand and discuss; this figure is compared with their current consumption and their reduction potential. The approach is described here.

5.5.1 The UK domestic 2050 target

The energy demand required to achieve carbon targets in the UK residential sector is a hypothetical figure that varies with the energy production mix and the range of carbon emissions from other sectors. This means that the energy demand requirement will be less restrictive if energy production and supply is de-carbonised. Assumptions on the future energy production and supply are made in energy scenarios in order to evaluate the future energy landscape; these are used here to analyse the viability of achieving 2050 targets in real family homes.

In order to quantify the 2050 target residential energy demand apportioned at a household level, assumptions are made about the future energy mix, the population size, the number of households and the proportion of electricity and gas; the evaluation is based on previous UK scenarios published by DECC and the Energy Saving Trust, and the parameters considered are summarised in Table 5.8.

A similar assessment was made by the 'Retrofit for the Future' project, which compared achieved energy demand reduction after physically implementing a number of building fabric improvements in a sample of dwellings against the 2050 target. The proxy target 2050 figure published by the Energy Saving Trust was 115 $kWh/m^2/year$ and 17 $kgCO^2/m^2/year$. This figure was based on the achievement of a 80% reduction in CO_2 from 1990 levels considering the performance for a standard three-bedroom semi-detached property normalised by the gross internal floor area for the same property type (The Technology Strategy Board, 2013).

Also, scenarios such as those published by DECC, set out a range of plausible trajectories to 2050 for each sector, and describe pathways that could accomplish the 80% emissions reduction target from 1990 levels. These pathways are based on a number of assumptions that restrict the energy demand target to be met, which also vary with expected $\mathrm{CO_2}$ emissions from energy supply sources. Table 5.8 shows the main assumptions within these scenarios, including: the number of households in 2050, the space heating and hot water consumption and the electric demand for domestic buildings. These assumptions are used to enable the estimation of a proxy demand target, which sets a hypothetical 2050 target tailored to each household.

Table 5.8: 2050 Energy demand figures from DECC scenarios.

Scenarios	**DECC:Nuc**	**DECC:CCS**	**DECC:Ren**
Number of households	40000000	40000000	40000000
Heating demand (KWh/y/household)	16657.5	17205	9122.5
Electric demand (KWh/y/household)	2337.36	1621.50	1234.80
Total consumption (KWh/m2)	189,95	188,27	103,57

The Energy Saving Trust target figure is within the range of the DECC scenarios; the demand figure from the higher nuclear scenario (Nuc) is least restrictive, at 190 $kWh/m^2/year$; the Nuc and the carbon capture and storage (CCS) scenario are less restrictive than that from the Energy saving Trust, at 188 $kWh/m^2/year$, whereas the renewable scenario (Ren) suggest the most challenging target, as low as 104 $kWh/m^2/year$.

The proxy tailored target, Q_{2050}, is calculated as follows:

$$Q_{2050} = 115 \cdot m^2 \tag{5.23}$$

Assuming a tailored energy consumption of 115 $kWh/m^2/year$ and applying it to the size of the house. This 'apportioned 2050 energy demand figure per household' enables the assessment of householders' role in achieving 2050 targets, following previous work (The Technology Strategy Board, 2013).

5.6 Summary

This chapter described the methodology applied to calculate tailored whole-house energy reduction, detailing the assumptions within the analysis. It presents a framework to evaluate the Reduction Effort Balance, which is aimed to reveal the impact of lifestyle measures compared to those that require an investment; the calculation method to quantify the impact of applying single reduction measures and the potential reduction that could be achieved if all measures are applied is presented.

The whole house energy reduction model developed in this chapter achieves the Objective 4 set in Chapter 1 by introducing a new framework, the 'REB' method, which is demonstrated in a sample of houses. As smart meters enter the market, the method can be applied to inform home owners about the energy reduction possibilities, their impact on energy consumption and the action required, either through lifestyle changes or investment. The method could also be applied on a larger scale to inform policy makers about the reduction needed from real homes to achieve the 2050 targets.

The methodology used to contextualise the reduction potential from family homes with a proxy tailored figure of 2050 targets is described, arguing the role of this comparison towards the second stage of the analysis, the interviews with householders. Chapter 6, presents the results of this analysis, discussing the possibility of family homes to achieve 2050 targets.

Chapter 6

Estimating the potential reduction

This chapter presents the results from applying the methodology detailed in Chapters 4 and 5 to seven family homes, in order to evaluate the impact of reduction measures. Household energy consumption is presented here and compared with published national figures (Department of Energy & Climate Change, 2012a), positioning the sample within the UK and evaluating household current CO_2 emissions, energy cost and energy consumption for gas and electricity. The results from this analysis are outlined and discussed in this chapter, and were then presented to householders in graphical form as part of structured interviews presented in Chapter 7.

6.1 Current energy consumption

A comparison between household annual consumption and the national figure for energy demand is presented here based on national data. The daily energy consumption is calculated by normalizing the annual data to generate a daily estimate, which is then compared with published values by apportioning the daily energy consumption from annual figures.

Gas consumption for space heating and hot water within the sample is very similar to the 2013 UK national figure, resulting in 50 KWh per day, which is only 3KWh higher than the national figure. Figure 6.1 shows the apportioned gas and whole house (gas and electricity) energy consumption for a day; Gas consumption in H09 and H37 is below the UK figure, whereas the rest of houses are above, especially H46 and H30 which are the highest consumers. H09's gas data was expected to be slightly lower due to the limited available data, which was recorded during the warmer portion of the heating season, as explained in Chapter 3; H37 gas consumption is lower than expected, especially taking into account that the data was influenced by the portion of the heating season considered; also, H39 energy consumption is lower than expected, as it is a detached solid wall house. H30, which is also a detached solid wall property, shows similar energy consumption to the UK national figure, considerably higher than the sample mean, as expected. In contrast to the gas consumption, sample houses show higher electricity demand than the UK national value, with H05, H09 and H37 the closest to the national figure, and H46 the highest consumer, almost three times higher than the national figure; H46 is also the household with the highest appliance ownership, owning 49 appliances. It was observed that within the sample the electricity consumption increases with appliance ownership. The slight deviation of the sample from the UK electricity consumption figure can be attributed to the fact that there are no low income family homes within the sample and there is partial occupancy during the week.

Within the sample households spend daily between £2 and £2.25 for gas and electricity respectively; gas is cheaper than electricity, assuming that the cost is £0.04 per KWh for gas, and £0.15 per KWh for electricity, (Department of Energy & Climate Change, 2015a). Despite the fact that space heating consumption only takes place in the winter and mid-term seasons, the gas cost apportioned for a day is still equal and in some cases, even higher (H05, H30, H39), than the electricity expenditure.

The CO_2 emissions from gas and electricity are shown in Figure 6.1. Figures are based on an estimate of gas and electricity emissions per KWh. These estimates are used here to compare current emissions with UK figures, even though the emissions will in reality vary depending on the energy source, transport losses and further factors. The CO_2 emissions derived from domestic gas consumption are assumed to be 0.203 Kg CO_2 per KWh and 0.527 Kg CO_2 per KWh of electricity. Emissions from photovoltaic panels are assumed to be 0 Kg CO_2 per KWh, neglecting emissions from the production of the PVs for the simplification of the analysis and for consistency with the approach taken with the other energy sources; the same is applied to the cost of electricity production from PVs, which is assumed to be 0, neglecting the initial cost of the panels.

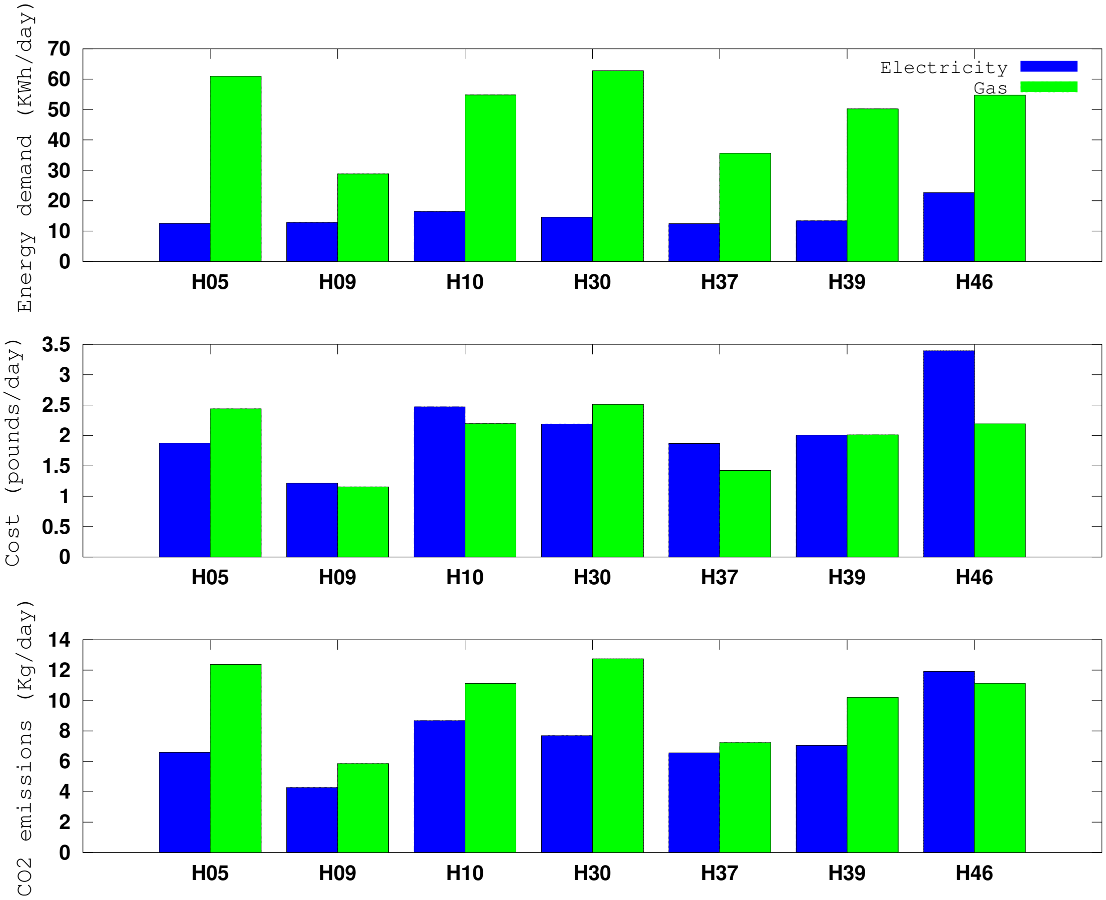

Figure 6.1: Annual energy consumption, expenditure and CO_2 emissions.

Space heating and hot water

Figure 6.2 shows the daily space heating and hot water energy consumption within the sample compared with 2013 UK figures. The space heating consumption is close to the national value, which is 39 KWh for the sample, and 38KWh nationally. The difference appears in the use of hot water, which is considerably lower, 4KWh, almost half the UK value. This could be linked to the temperature to which the hot water is heated, which was observed to be much lower than results from the Energy Saving Trust (Energy Saving Trust, 2008a); the Energy Saving Trust suggests a mean temperature of 52℃, 7℃ higher than that found in the sample.

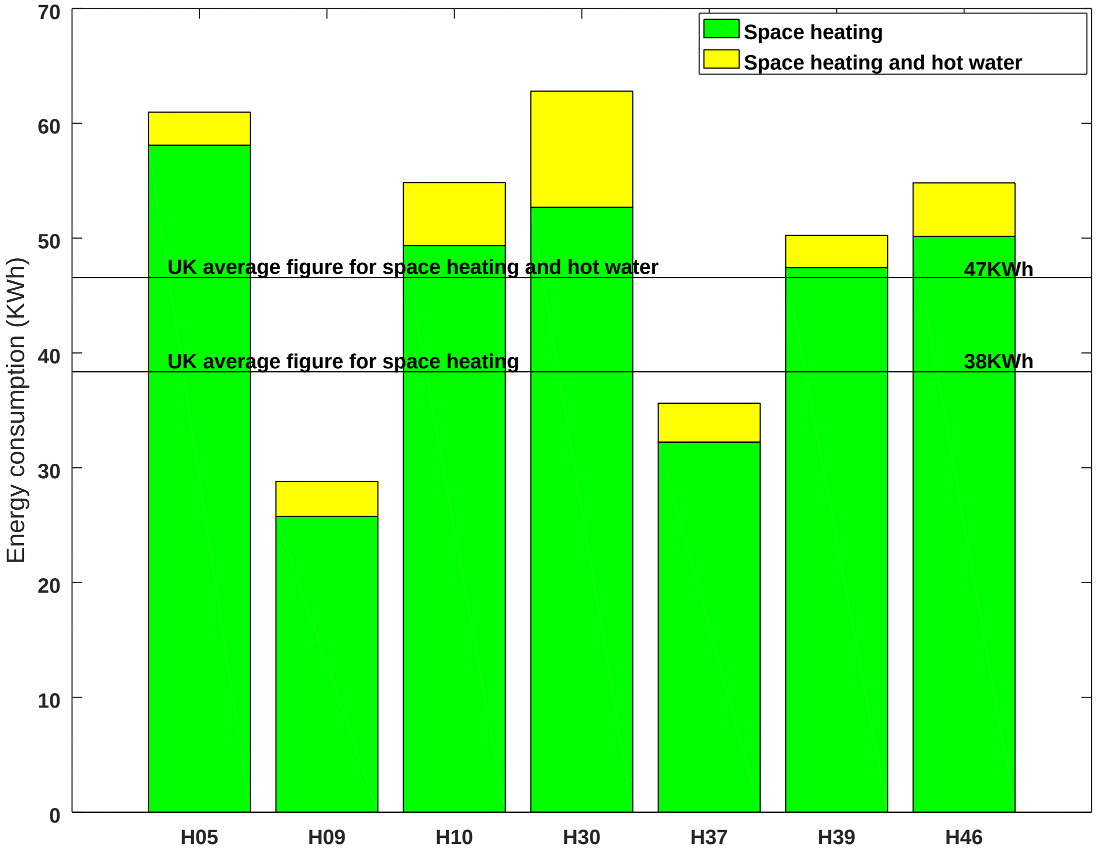

Figure 6.2: Space heating and hot water daily energy consumption in 2013.

The daily indoor temperature when the space heating is on ranges from just over 17℃ in H30 to over 20.5℃ in H46. H05, H10 and H37 daily average temperature is between 18.5 and 19.5℃, whereas H09, H30 and H39 temperature varies between 17℃ and 18℃. Looking for general patterns of energy consumption, Figure 6.2 and Figure 6.3 show differences in indoor temperature which can be linked to gas energy consumption. For example, in H09, where daily average indoor temperature is below 18℃ and energy consumption is the lowest; this does not apply for H30, where energy consumption seems very high for the given daily indoor average temperature. Other considerations should be taken into account to understand space heating consumption, such as insulation levels, the time space heating is switched on for and windows opening, which will also impact on energy consumption as can be seen in Figure 6.4, and Figure 6.5.

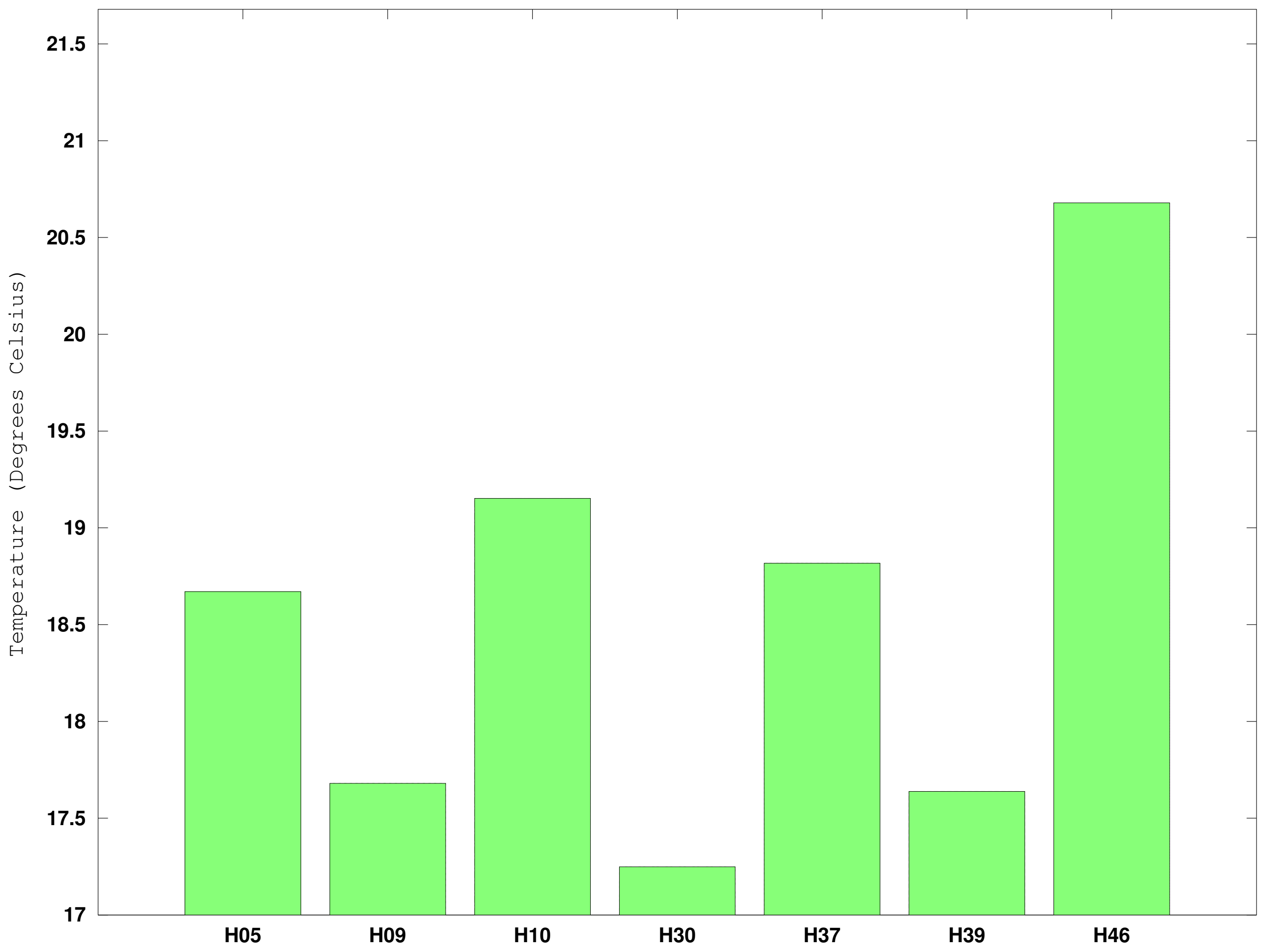

Figure 6.3: Household daily indoor average temperature over a 24 hours period when the space heating is on.

The period of time when the space heating is on over the day is shown in Figure 6.4 in minutes. As can be seen, H05 is the household with the longest heating period, followed by H09, H46 and H10. This can partially explain why the energy consumption in H05 is high despite its low daily average temperature. The daily on time varies from nearly 150 min per day in H30 to over 400 minutes per day in H05.

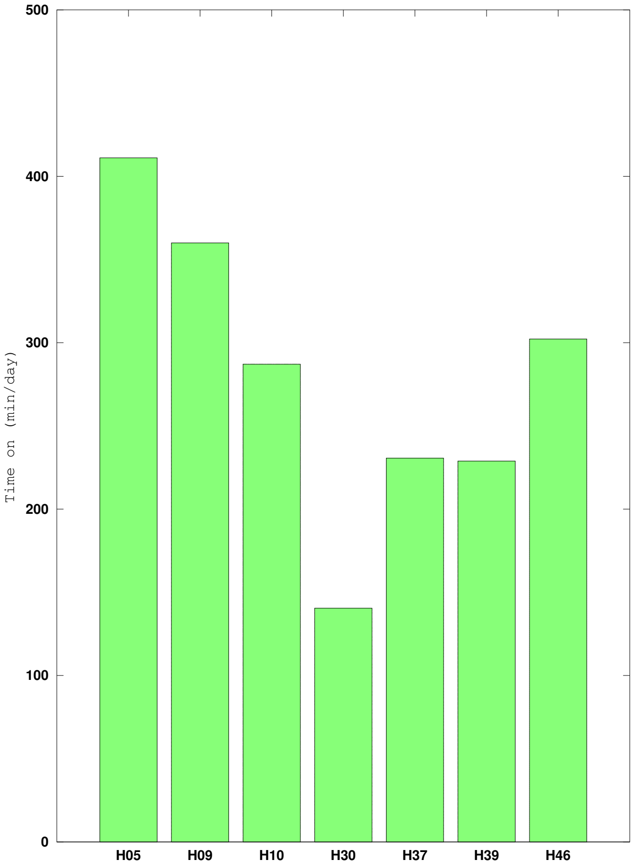

Figure 6.4: Household daily average heating period.

Figure 6.5 shows the daily opening time per monitored window in each house. Although the window position data is limited by the fact that not all the windows were monitored and the number of monitored windows was not consistent in the sample, interesting differences between households can be observed by looking at the daily opening time per monitored window. H05 is the household where windows are opened for the longest, just below 350 minutes per day and monitored window; the windows opening in H05 slightly decreases when the space heating is on, suggesting that windows are left open when the central space heating is on. This observation supports previous observations on windows opening behaviour (Offerman et al., 2007; Price and Sherman, 2006). The rest of households show a different pattern, being the length of windows opening time higher when the heating is off. The opening rates in H10 and H46 are the lowest, 150 minutes per day, and just below 100 minutes for days when the heating is on, whereas for the rest of houses, the openings vary between 150 and just over 300 minutes per day. The length of time when windows are opened is one behavioural parameter that impacts on the dwelling's air change rate, but in this study, and given the limitation of the monitoring data, the relationship of monitored windows opening with wind speed and air change rate was found to be poor, also other behavioural parameters that heavily impact on the output ventilation rate, for example the width of the opening or the effect of opening multiple windows, were not evaluated (Cosar-Jorda and Buswell, 2015). Furthermore, individual radiators on timings and their location in the house could add interesting information to the relationship between windows opening and energy consumption.

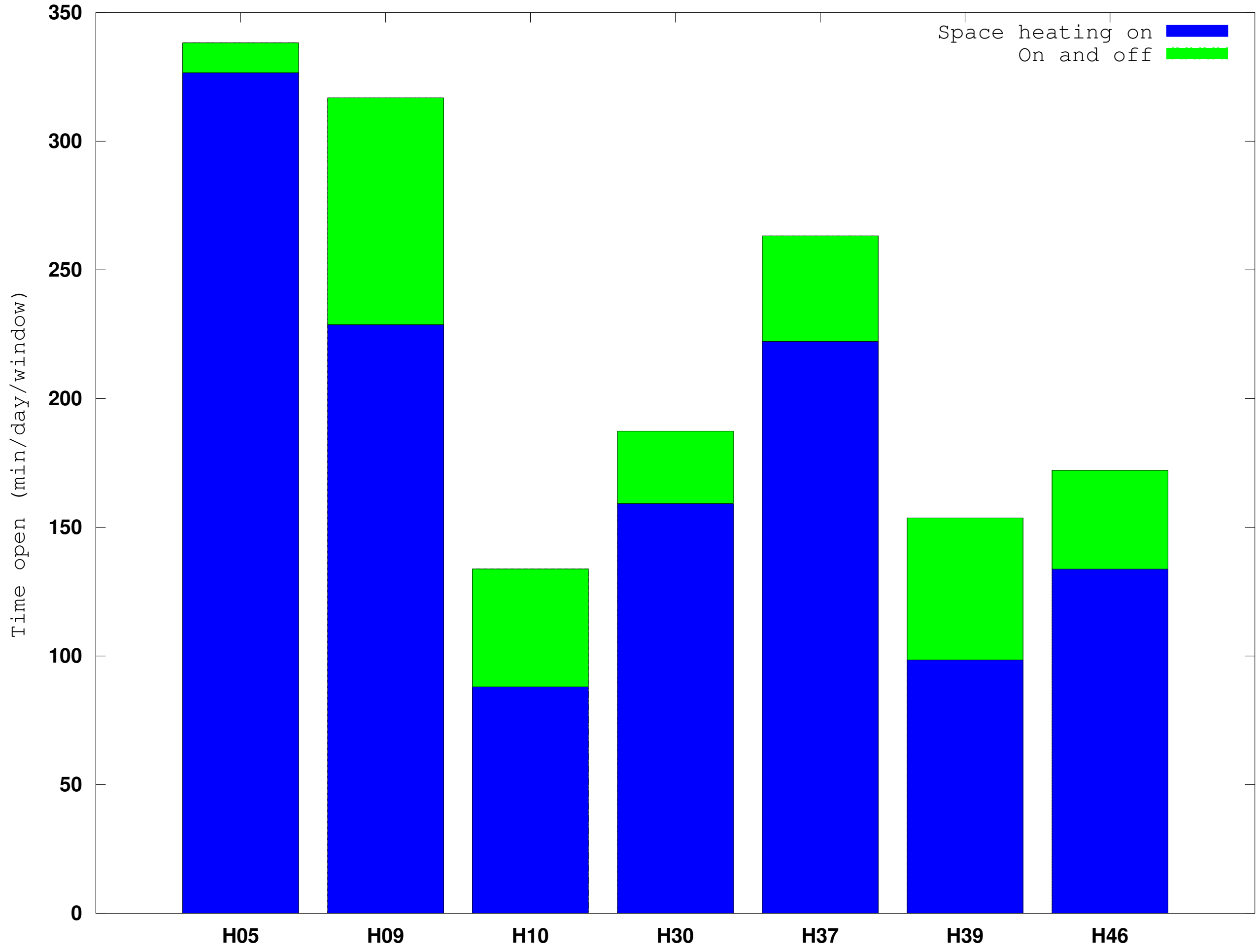

Figure 6.5: Household daily average opening time per monitored window (over24 hours).

Electricity consumption

The daily electricity consumption for the sample homes is higher than the UK figure. Figure 6.6 shows the electricity consumption for 9 categories that includes every household end use appliance (laundry, cooking, cold appliances, ICE, lighting and other devices). As can be seen in Table 5.4, Chapter 5, monitored loads represent between 42% and 91% of the electric consumption in H05 and H46. Differences in monitored loads make it difficult to conduct a straight forward comparison between appliance categories without applying further assumptions. The approach has been to homogeneously distribute unknown loads between the identified categories and apply this assumption to the electricity data as explained in the previous chapter. Assigning electricity consumption to categories in this way aims to provide insight into the energy consumption associated with specific practices in the house, such as consumption associated with laundry consumption which for example is particularly high in H46, representing over a third of the electricity consumption; cold appliances loads are especially high in H39.

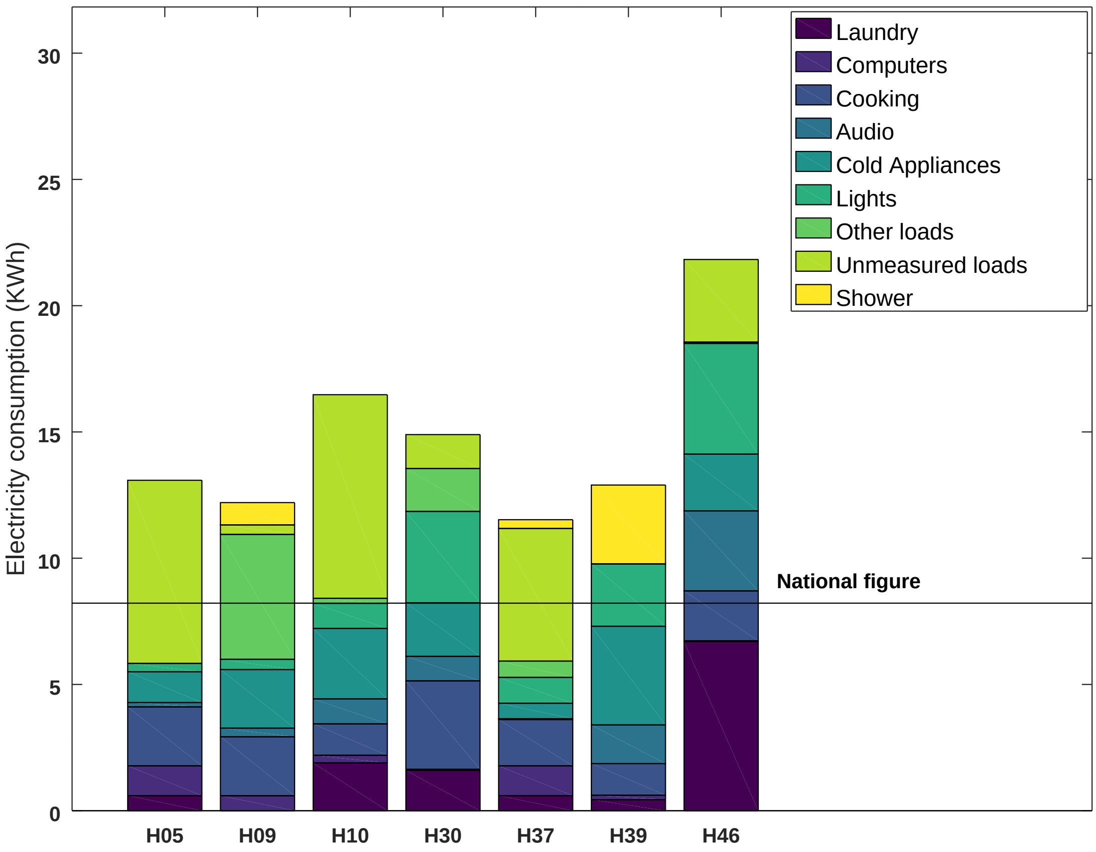

Figure 6.6: Electricity distribution in categories.

6.2 Reduction analysis results

The impact on energy consumption predicted from applying individual measures is evaluated in this section. Measures are presented ranking the results from those that have the highest impact overall to those that have the lowest impact. Results from the 'Reduction Effort Balance' are also presented, evaluating the reduction proportion that can be achieved though replacement, retrofit and lifestyle change.

6.2.1 Impact of energy measures

The energy reduction ranking from each measure applied in isolation is summarised in Table 6.1 and discussed in the following subsections. The ranking is based on the average impact of each reduction for the sample evaluated, highlighting the sample minimum, maximum and mean figures in Table 6.1.

Table 6.1: Percentage of energy reduction measures in rankorder.

Reductions (% of Energy Consumption)	**Category**	**H05**	**H09**	**H10**	**H30**	**H37**	**H39**	**H46**	**Minimum**	**Maximum**	**Average**
Wall insulation	Retrofit	9.0	11.6	15.9	34.2	10.4	60.8	4.5	4.5	60.8	**20.9**
Triple glazing	Retrofit	9.1	23.0	21.8	21.4	16.9	13.7	19.8	9.1	23.0	**18.0**
Heating to 17℃	Lifestyle	18.0	11.4	18.6	14.3	17.5	9.4	25.1	9.4	25.1	**16.3**
In use heating	Lifestyle	15.5	14.5	19.2	16.9	16.6	7.4	20.0	7.4	20.0	**15.7**
Ventilation	Lifestyle	31.1	9.1	0.7	16.9	16.0	4.4	9.0	0.7	31.1	**12.5**
New boiler	Retrofit	7.1	12.6	4.2	5.5	4.5	14.6	3.0	3.0	14.6	**7.4**
Floor insulation	Retrofit	11.1	5.5	5.8	3.4	5.2	4.1	6.3	3.4	11.1	**5.9**
Sealing	Retrofit	4.0	7.2	3.3	2.4	6.4	2.5	4.2	2.4	7.2	**4.3**
Loft insulation	Retrofit	0.5	0.3	0.3	7.8	3.8	0.5	4.6	0.3	7.8	**2.5**
No heating over 15 ℃	Lifestyle	4.4	3.1	1.7	2.5	2.2	1.4	1.7	1.4	4.4	**2.4**
Heating when home	Lifestyle	4.4	4.9	0.0	0.0	5.4	0.9	0.0	0.0	5.4	**2.2**
New laundry appliances	Replacement	0.0	0.0	1.0	0.0	0.0	0.0	1.0	0.3	7.8	**2.5**
Insulated door	Replacement	0.8	2.9	1.2	0.8	2.4	1.2	3.6	0.8	3.6	**1.8**
No tumble drying	Lifestyle	0.0	0.0	1.3	1.3	0.0	0.0	7.2	0.0	7.2	**1.4**
One fridge-freezer	Lifestyle	0.4	3.8	1.7	0.0	0.6	1.5	0.0	0.0	3.8	**1.1**
New cooking appliances	Replacement	1.2	1.3	0.5	0.7	1.0	0.4	0.4	0.4	1.3	**0.8**
New fridge-freezer	Replacement	0.4	0.8	0.9	0.4	0.3	0.9	0.4	0.3	0.9	**0.6**
Replace bulbs	Replacement	0.3	0.3	0.4	1.0	0.3	0.8	0.4	0.3	1.0	**0.5**
New media equipment	Replacement	0.4	0.4	0.3	0.2	0.5	0.4	0.5	0.2	0.5	**0.4**
No standby loads	Lifestyle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**

Wall insulation

External wall insulation has a particularly high impact in two houses, H30 and H39, which are both detached properties with solid wall construction. The potential reduction is as high as 60% in H39, and just over 34% in H30. The difference between these two solid wall houses is attributed to the low indoor temperature and the length of space heating period found in H30, which are the lowest within the sample and which can be the reason why improving the thermal insulation of the dwelling might not have as high an impact as expected for a solid wall house. In the rest of households, adding wall insulation could decrease the energy consumption between 5 and 15 %.

Triple glazing

The update of windows to triple argon filled glazing could reduce energy consumption from 9% to up to 23%. The biggest reduction is possible in H09, where the glazing area is significant; the lowest impact is in H05, a semi-detached house with a reduced glazing area. The potential impact from this measure ranges from 13 to 20%.

Heating up to 17℃

Similar reductions to those from triple glazing are possible from reducing the peak indoor temperature to 17℃ . The maximum reduction is possible in H46 as can be expected considering their average daily temperature, which is over 21℃ during the heating season, the highest from the sample. This is followed by H10, H37 and H05, whose average temperature ranges between 18.5 and 19.5℃ . H30 and H09 potential reduction is 14% and 11%, their current average temperature being just over 17℃ , very similar to H39.

In use heating

The impact of heating only occupied rooms instead of central heating the whole house is as high as 20% in H46 and H10 and as low as 7% in H39, being in the other cases between 14% and 16%. This high reduction is linked to the impact of the weekly occupancy profiles, as in the sample, the households are generally occupied during the week at least by one person. Heating only the occupied room during the working time in weekdays has a high potential to reduce space heating consumption.

Ventilation

The decrease of ventilation to the minimum standard described in Chapter 5 could reduce energy consumption by up to 31% in H05, where windows are opened daily on average for the year around 350 minutes per window, this figure being only 10 minutes shorter during heating days; H37, which also shows long window opening time periods, around 250 minutes per window, could also reduce 17%, as in H30 where opening length is just below 200 minutes per day; H09 and H46 could reduce their consumption by 9%, showing current daily window opening of 150 minutes per window (in the heating season). H10's possible reduction is very low, only 1%, being the house with the shortest window opening time, only 100 minutes per day, which is 66% lower than in H05. All houses except H05 show shorter opening times during heating days; in H05 the opening time is very high, and a significant reduction could be achieved if their current practices were changed.

New boiler

The replacement of the boiler could lead to an energy reduction of up to 15 % in H39, which has the most inefficient boiler in the sample. The minimum reduction is achieved in H46, as they already have an efficient boiler and therefore only 3% reduction would be possible.

Floor insulation

The addition of floor insulation to best standard levels could reduce energy consumption to up to 11% in H05, a house which was built in the early 40s and where the floor is suspended timber. In all the other houses all with solid concrete ground floors have the potential reductions range from 4 to 6%.

Sealing measures

Sealing intervention results suggest very similar reductions within the sample, ranging from 4 to 7 % of the energy consumption. This is attributed to the simplicity of the approach, which applies assumptions to the building characteristics to determine the infiltration rate.

Loft insulation

The impact of loft insulation is especially significant for H30, which during the monitoring period did not have any insulation. The insulation of the loft could reduce the energy consumed in H30 by 8%, whereas in the rest of houses, where the insulation thickness was already quite high, particularly in H05, H09, and H10, the impact of this measure was insignificant.

No heating over 15℃

Reductions from switching off the heating when the temperature outside is above 15℃ could reduce energy consumption from 1% in H39, to 4 % in H05, suggesting that within the sample, the heating is switched off quite early during the middle-seasons.

Heating when home

Switching off the heating when the house is not occupied is not a key reduction within the sample, as households are occupied during the week most of the time. No reductions were possible in H10, H30, and H46, unless there were a change in their current lifestyle and working patterns; this reduction would have an impact in H05, H09 and H37 reducing their consumption by 5%.

Insulated door

The replacement of the entrance door could reduce energy consumption by updating the door with a higher insulated one; this reduction has a potential ranging from 1% in H05, H10, H30 and H39 to 4% in H46.

Replacement of appliances

The replacement of appliances for the most efficient ones on the market will impact energy consumption depending on the efficiency improvement of the current appliance and on householder usage, i.e. appliances frequently used will have a higher reduction impact overall. Energy reduction results are very low and none of the replacement reductions surpass 1%. The highest energy reduction is possible from new cooking appliances, followed by the update of cold appliances, laundry electric appliances, and LED lights. Overall, replacements seem to be insignificant for energy reduction, even for whole house energy expenditure, as although electricity is more expensive, the percentage reduction is still very low.

No tumble drying

The use of the tumble dryer within the sample is not frequent; H39 does not have a tumble dryer and the rest of households hardly ever use it. The exception is H46, where the reduction potential is as high as 7%.

One fridge-freezer

All houses except H46 and H37 have more than one refrigerator; H05 has a second refrigerator which was generally switched off over the period of study; H30 reduction was not evaluated as the second freezer was not monitored. In H09, H10 and H39 the second fridge freezer reduction potential ranges from 1% in H39, to 4% in H09.

No standby loads

Standby loads were identified to be irrelevant for whole house energy consumption, as in all cases, reductions represent just above 0%. It should be noted that the evaluation of these reductions is limited as standby loads are not fully represented, as only monitored ICE devices are accounted for.

6.2.2 The REB potential

Grouping the measures listed in Table 6.1 and re-running the model frames the results in terms of lifestyle, replacement and retrofit. Figure 6.7 shows the potential reduction for each category and, as it can be seen at a first glance, replacing appliances has a reduced impact in all households, the highest reduction being 5% in H46 and as low as 1% in H05, H10, H30 and H39.

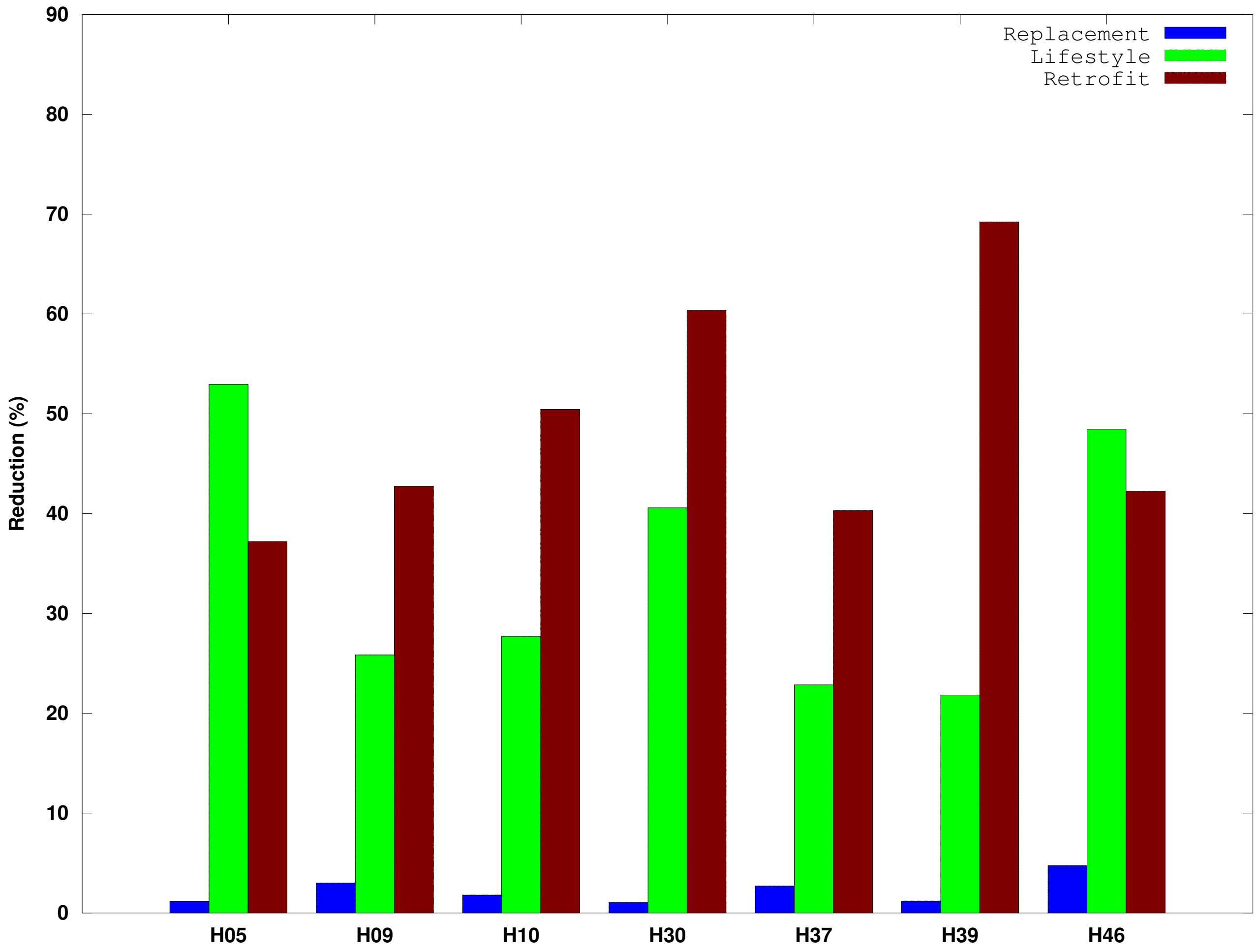

Figure 6.7: Reduction Effort Balance results.

The impact of lifestyle measures is especially high in H05, where they can lead to up to 53% reduction; H05 and H46 are the only households where the potential reduction from lifestyle measures is higher than for retrofit measures. Retrofit could lead to up to 60% and 69% reduction in H30 and H39 respectively. In H39 the high potential energy reduction is mainly accredited to the solid brick walls. However, in H30, it is the result of a combination of unfavourable building characteristics, i.e. no loft insulation, old glazing, and solid walls.

Lifestyle measures achieve, at least, reductions over half of those possible from applying retrofit measures, except in H39, where average indoor temperature is one of the lowest, occupancy during the week is very low and their ventilation practices do not appear to highly impact on energy consumption. The lifestyle potential reduction in H05 is the highest, being just over 50%. This is attributed to their ventilation practices and space heating duration which contribute to maintain a mean indoor air temperature while having a high ventilation rate. A reduction on ventilation could easily achieve an energy reduction while ensuring air quality, alternatively they could switch off the space heating when the windows are opened to avoid ineffective space heating energy consumption.

The REB shows the varying impact of applying measures in real households, where differences in building characteristics, householder occupancy, householders' temperature choice, ventilation, space heating practices, and appliances consumption determine the most successful measures to be applied in each specific home. Results suggest that sample households could achieve 2050 domestic energy demand figures by either applying lifestyle or retrofit interventions, or in some cases a combination of both, as in H05, which could only achieve the aimed reduction if they applied at least some of the lifestyle changes, and in H30 and H39, which would only achieve the target if they invest money in retrofitting. H09, H10, H37 and H46 could achieve 2050 domestic targets by applying either retrofit or lifestyle measures.

6.2.3 Whole house energy reduction

Results from the model suggest that achieving the 2050 figures are possible. The domestic energy target could be achieved if the combination of measures were attractive to householders, as it is shown in Figure 6.8. The model suggests that all households could hypothetically achieve lower consumption than that needed for 2050 targets. The results from retrofit measures suggest an average 49% reduction. This figure is lower than that found by Banfill et al., who found a potential reduction of 64% after modelling a whole house retrofit intervention in a 1930s semi-detached house (Banfill et al., 2011b). The retrofit potential from the solid wall houses in the sample, H30 and H39 is very close to the figure suggested by Banfill and the Swedish BETSI project (Mata et al., 2010), partially as the house characteristics are similar to those from the houses previously studied.

Considering lifestyle, retrofit and replacement measures, energy consumption within the sample can be reduced from 66% in H37 to up to 81% in H39. Optimistic results that suggest that 2050 targets can be met by every home in this sample.

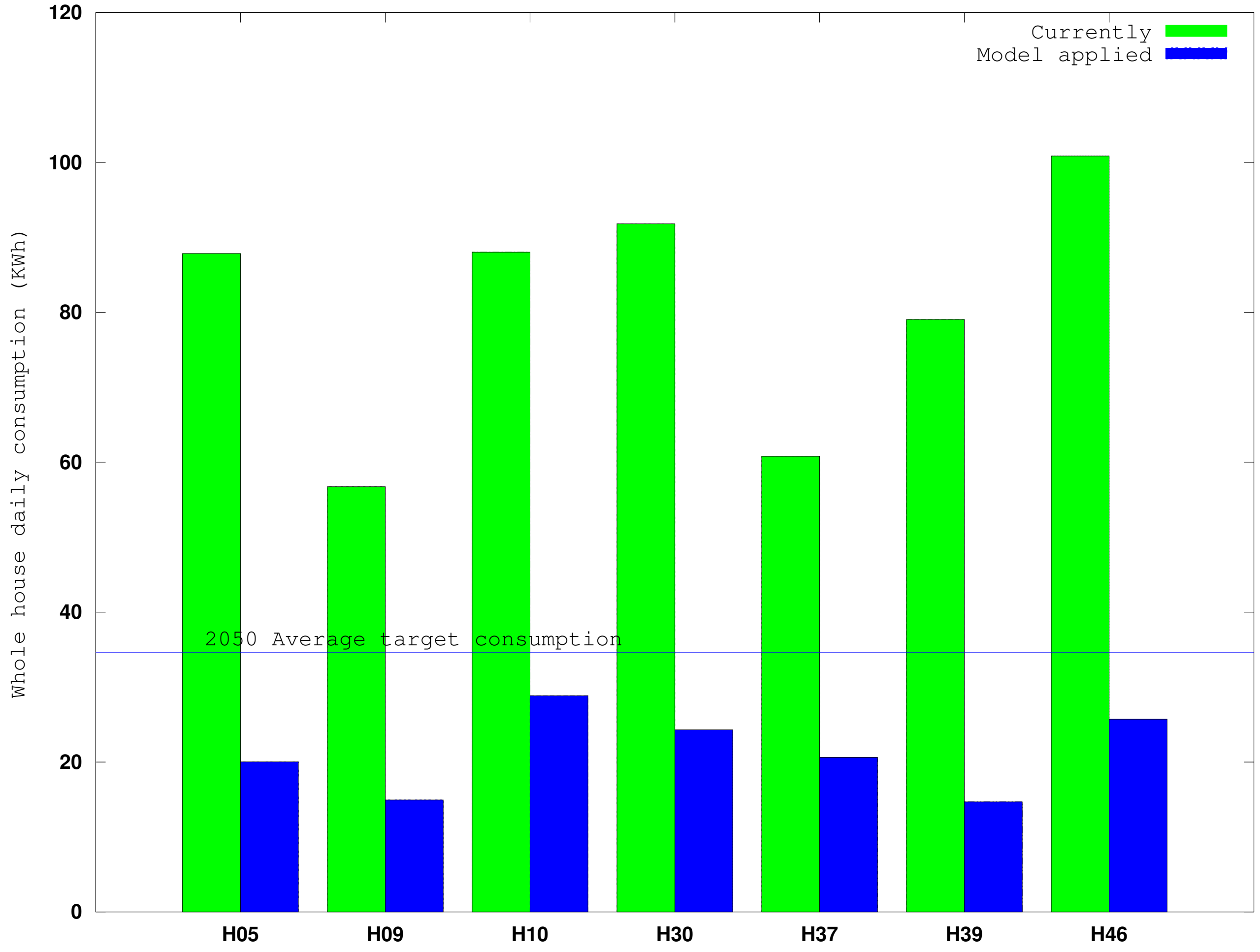

Figure 6.8: Potential reduction and 2050 target.

6.3 Summary

A detailed evaluation of the impact from reduction measures on family homes shows the differences between households on the potential reductions. These findings support previous work which suggest that the complexity of domestic energy demand needs to be understood as a socio-technical issue. Reductions reflect the impact of building characteristics, householders' temperature choice and other participant behaviours that influence space heating demand, such as heating period and windows opening time. The analysis suggests that the potential reduction from the replacement of devices is less important than behavioural measures to delivering energy reduction in relation to 2050 targets, raising the significance of promoting feedback from independent sources to contextualise the information given by the appliances market, in order to help householders prioritise the most effective reduction measures for their household, especially if they require investment.

Results from applying lifestyle measures reflect the variety of reductions that can be achieved without capital investment and their impact range, which is dependent on how energy is currently consumed in each individual home. Results suggest that retrofitting options are specially relevant for poorly insulated dwellings, but their impact are also dependant on space heating settings and so their evaluation should be tailored to the household, taking into account existing heating practice usage in order to reduce over estimation of likely energy reduction.

The reduction potential from ventilation routines is one of the highest, emphasising the importance of treating the potential reduction in relation to current ventilation practices. The ventilation level considered in this evaluation is hypothetical, reflecting the maximum reduction achievable to accomplish health standards. Although this could only be achieved with a mechanical ventilation system, it does reflect current ventilation practices and their impact on energy consumption, offering an approach that can be developed further to analyse the impact of other ventilation routines.

This chapter attains the Objective 5 set in Chapter 1 by evaluating the different impact that energy reduction measures have in household energy consumption. The analysis suggests that the potential reduction from the replacement of devices are less important to delivering energy reduction in relation to 2050 targets. The drivers of action that carry energy implications are specific to each household and can only be examined at the household level, evaluating the different motivations and path ways to achieving energy reductions. Overly simplified assumptions in retrofitting studies applied to one size fits all solutions can therefore lead to ineffective and costly policy decisions, whereas the impact of changes in householders' lifestyle might be overlooked in policy decisions, especially for ventilation practices, regardless its energy impact.

The results suggest an optimistic view of what can be achieved in family homes, where energy reduction is possible by applying a number of measures. There is flexibility in the application of these, thus easing the burgeon on households' decision making regarding which measures to prioritise. 2050 figures can, in most cases, be achieved by either investing money in highly efficient appliances combined with retrofitting the house or changing current levels of comfort and service.

The question that remains, however is to what extent householders might choose to apply the reduction measures, as this is one of the key challenges to achieving home energy reduction, explored in the following chapter.

Chapter 7

Qualifying energy reduction

This chapter describes the qualitative data collection, presenting the objectives of the interviews and the methodology utilised to analyse the results. The emerging themes are described, together with the insights from the interviews. The methodology was developed to quantify the impact of measures that are acceptable to householders, by revisiting the modelling assumptions previously applied in order to estimate the likely energy reduction in family homes and to understand the more complex conditions that are sometimes needed in order for measures to be applied.

7.1 Data collection design

The study involved face-to-face semi-structured interviews in participants' homes to enable a familiar context, and help participants recollect their daily routines (Kujala, 2003). This was also convenient to the participants. The semi-structured interviews were designed to engage participants with their tailored energy consumption information and explore their opinions and interest in applying reduction measures. A set of graphs were used to present households with their historical monitoring data which were used alongside a set of semi-structured interview questions which were used to understanding the specific routines of the household that impact upon energy consumption.

Modelled reductions were then presented in order to evaluate householders' willingness to apply them, and in order to understand the barriers to implementation measures and the potential role of smart home technology to enable change. The interview questions are in Appendix C; the design of the interview is explained in this chapter. The interview was designed to answer the main research question still remaining from the quantitative analysis: which measures are householders willing to apply in their house and to what extent?

The interview was divided into three sections: contextualisation, task and discussion.

Table 7.1 summarises each section activity and its purpose within the approach.

Table 7.1: Interview methodology outlined.

Section	**Activity**	**Purpose**
Contextualisation	Introduce study	To explain the interview purpose, outline the activities, gain permission for audio taping and inform about data confidentiality.
	Gather the householder's interest in energy demand reduction	Understand householders' motivations to reduce energy consumption. Did householders know about the 2050 measures? Do they feel these targets are relevant to them? What is the main reason for their interest on reducing energy?
	Discuss their interest in 2050 figures	
	Discuss their interest in energy reduction	
	Discuss the plausibility to achieve tailored reduction.	Are householders optimistic about achieving them? If not, why?
	Energy reduction measures ranking	Gather householder ideas regarding energy measures that would help them decrease their demand; what measures are familiar to them? Do they know which have the highest potential to reduce energy?
Task	Presentation of model results	Presentation of their reduction potential compared to 2050 targets. Do they think their tailored results are plausible? Do they think they are truthful?

Section	**Activity**	**Purpose**
	Ranking of modelled measures	Understand which modelled measures were not familiar to householders. Analyse householders' perceptions on the energy reduction potential of each measure. Gather reduction ideas from participants and evaluate if they are modelled and if not if they can be modelled. Are modelled measures listed in the participants ranking? If not, did they know about them? Did householders rank measures correctly ? Are there any assumptions that need to be revisited in the model?
	Compare rankings	
	Ascertain their willingness to apply reduction measures	
	List barriers preventing householders from applying changes	
	Evaluate the time frame for reductions to take place	
	Present the REB approach	Analyse the REB approach suitability. Is it relevant to householders?
	Discuss the relevance of REB	
Discussion	Evaluate householders' opinions regarding the data provided	Gather people thoughts on their tailored data, is the information given relevant to householders? See how the information changed their personal views on energy reduction, how feasible they think is to reach 2050 targets, and if there was some energy related issue that they missed in the discussion.

7.1.1 Part 1 : Contextualisation

The first part of the interview contextualised the study by presenting to householders their tailored 2050 energy demand targets. Participants were informed about their tailored energy reduction towards 2050 energy consumption targets by showing them Figure 7.1. Looking at the graph, participants were asked: ‘How realistic do you think it is to get to 2050 target energy demand savings?’

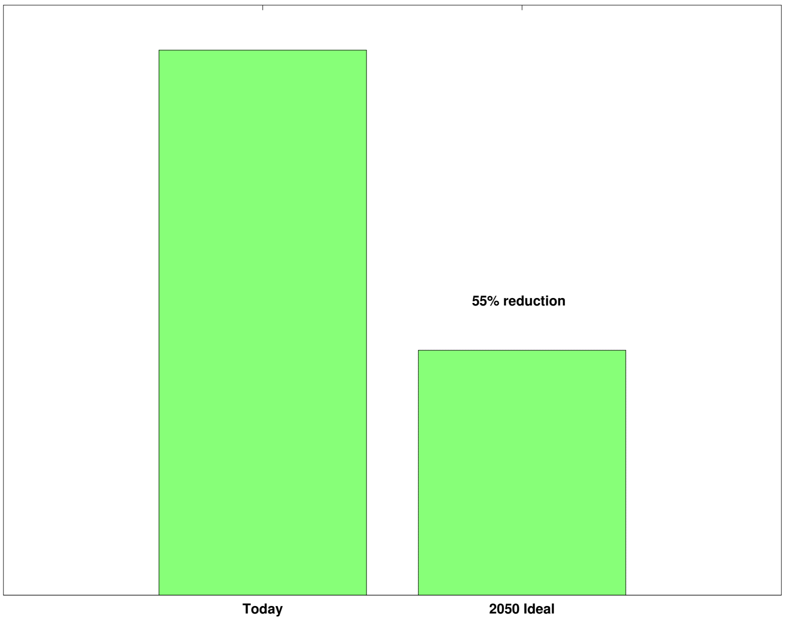

Figure 7.1: H39 Intended reduction towards 2050.

Once the 2050 target was presented, participants were asked for reduction measures that would potentially decrease their energy consumption and they were invited to write down each idea on a different note; when they finished, they were challenged to rank reduction measures by their energy potential. Figure 7.2 shows an example of the activity results. The notes are pink for FA and green for MA participants, they are numbered by both adults as a team exercise to rank first those measures that save more energy.

7.1.2 Part 2: Task

The core of the interview answered the following questions: Which measures are householders willing to implement? What are their barriers to implementing reduction measures?

Householders’ willingness to apply reduction measures was evaluated by showing them their

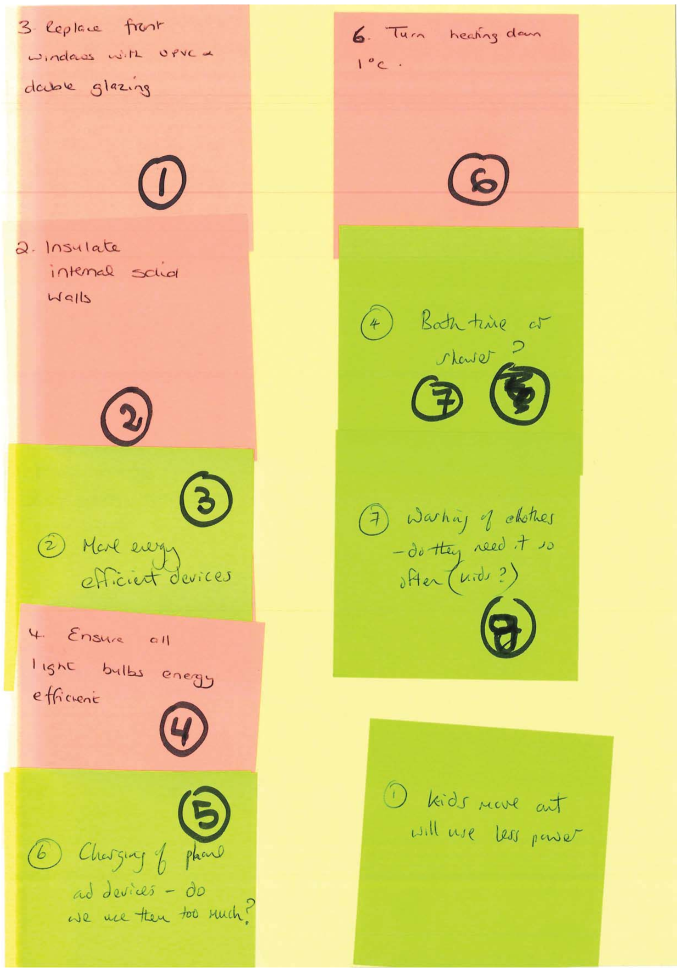

Figure 7.2: H39 Participants energy reduction ideas.

total household reduction and the potential of each measure applied in isolation. Figure 7.3 shows the potential household demand reduction against 2050 targets, which was presented to participants to initiate the discussion around whether or not the modelled reductions were achievable. Each individual measure was discussed by looking at the ranking shown in Figure 7.4; householders willingness to apply measures was questioned, discussing if any condition would be needed to apply reductions. Answers were recorded as follows:

- I have already applied it;
- I will do it;
- I only would do it if... (explain condition);
- I am not going to do it because.

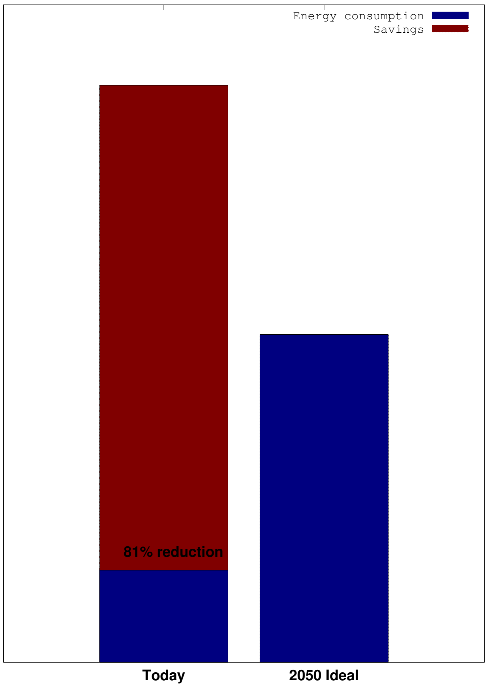

Figure 7.3: Potential demand reduction against 2050 targets for H39.

If the householder considered implementing it, with or without further conditions, the time frame was explored, choosing between:

- today (0-6 months);
- Near future (1-5 years); or,
- Long term (over 5 years).

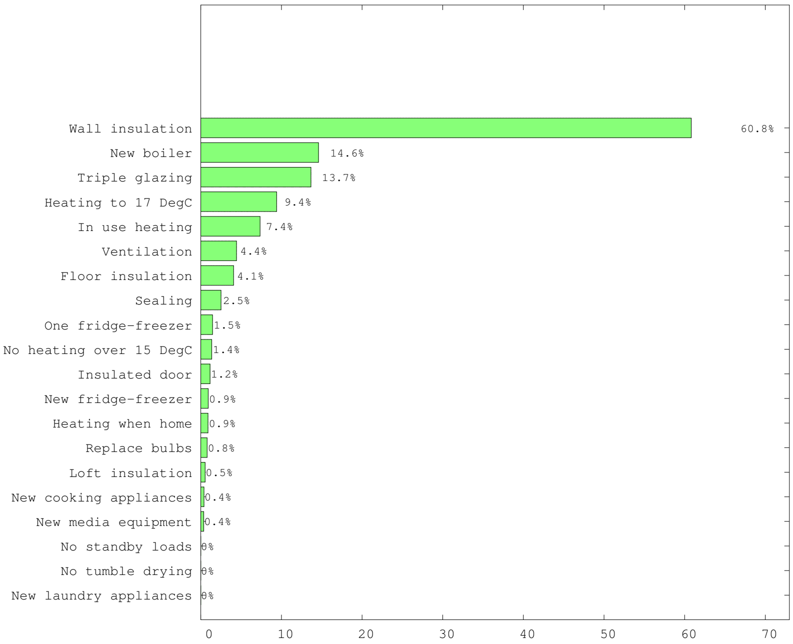

Figure 7.4: Energy demand reduction ranking for H39

Assumptions within the model were explained and discussed to evaluate their suitability. Once all measures were discussed, the 'REB' categorization was presented and explained, as shown in Figure 7.5.

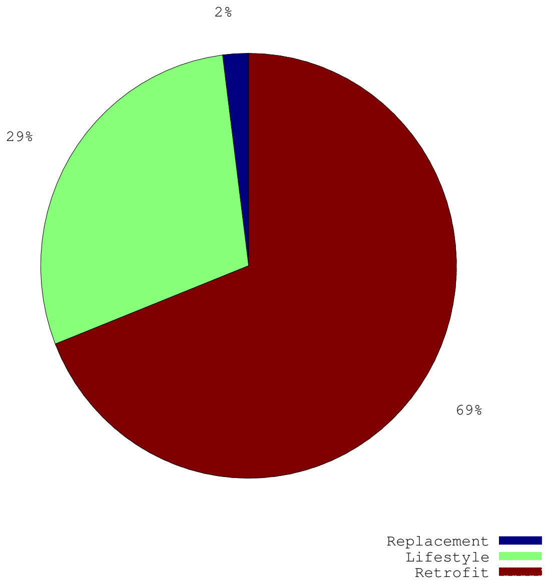

Figure 7.5: H39 REB.

7.1.3 Part 3: Discussion

During the interview, questions were asked to raise key discussion points. These were: participants interest in applying energy reduction measures and 2050 targets; the relevance of the visual data given to the participants; the role of the REB categorisation for householders; barriers stopping householders from applying the measures and the potential role of home innovation to enable change.

7.2 Qualitative data analysis

Insights from the interviews are discussed here and the thematic analysis described, together with the emerging themes.

7.2.1 2050 target

Participants in H05, H09, H10, H37 and H46 were not aware of the 2050 domestic energy consumption target, except H37MA[1], whose job was linked to building energy research, H30FA and both participants in H39 were aware about the global CO_2 issue, although they were sceptical about the domestic sector's role in achieving the Government's target, arguing the importance of industry's action; H05FA showed disinterest due to the 'Government's continuous change on targets'.

Household 2050 intended reductions were considered viable in H09 and H37. H10MA, AH10FA, H46MA and H46FA, agreed it was a high reduction, but possible if they made a big investment; H05MA and H30FA hesitated, finding it difficult to evaluate a target which was over 30 years ahead. H39MA and H39FA found it difficult to achieve further reductions because they considered their routines to be as low energy consuming as possible.

The main reason for the householders aiming to reduce their energy consumption was cost, which was unanimous across the participants. The participants from H05, H30 and H37 also mentioned the importance of reducing the impact of energy consumption on the environment, and H39 participants reported wishing to decrease energy consumption to reduce waste and as part of their children's education.

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[1] MA: Male Adult

7.2.2 Reduction measures

Householders reported a number of ideas about how to reduce energy consumption ranging from 4 to 22 ideas across the sample. Participants ideas are listed in Table 7.2. These are categorised in nine groups: use less electricity, insulation, lighting, in use heating, reduce indoor temperature, ventilation, new appliances and systems, hot water use and smart home technology.

Table 7.2: Householders' initial energy reduction ideas.

Categories	**Householders' ideas**	**Participant's contribution**
Use less electricity	Use less appliances	H05MA
(ICE)	Limit time of use of TV, laptops and tablets...	H30FA, H46FA
	Use kindle instead of iPad when reading (less lighting)	H30FA
	Charging phone and devices less often	H39MA
(lighting)	Turn off lights	H46FA, H46MA
	Turn off lights when not in use	H09MA
(cooking)	Use cooker top hob and gas cooker instead of switching on electric oven	H30FA
	Boil only once the kettle	H37FA
	More efficient use of oven	H30FA
	Use oven only for the duration needed	H46FA
	Use kettle only once per cup	H30FA, H46FA
(standby)	Cut down on standby	H46FA
	Turn off electronic devices when not in use (laptops...)	H30FA
	Turn off household devices at mains (over night)	H30FA
	Switching appliances off not leaving standby	H37FA
	Switch standby loads off (turn off from plugs)	H09MA
(laundry)	Stop using the tumble dryer	H30FA
	Fully load washing machine	H37FA
	Dry outside instead of tumble	H37FA
	Use cooler clothes washing temperatures	H30FA
(other)	Remove unnecessary freezer	H30FA
	Put extractor fan on a timer	H30FA
Insulation	House insulation	H05MA, H09MA, H10MA, H30FA
	Windows with a higher thermal performance	H09MA, H46FA

Categories	**Householders' ideas**	**Participant's contribution**
	Line curtains to keep heat in	H10FA
	Improve loft insulation	H30FA
	Add external wall house insulation	H30FA, H46MA
	Install triple glazing on windows	H37MA
	Add external door insulation	H30FA
	Replace front windows with UPVC and double glazing	H39FA
	Insulate internal solid walls	H39FA
	Triple glazing	H30FA, H46FA
Lighting	Energy efficient lights	H05MA, H39FA
	Changing halogen lights to LED	H10FA
	LED lights	H30FA, H46MA
In use heating	Use the heating in less rooms	H09FA
	Wood burning stove instead of central heating	H10FA
	Heat only living room (use wood burner)	H30FA
	Only heat rooms in use	H30FA
Reduce indoor temperature	Put on more clothes (less heating)	H09MA
	Turn down central heating temperature	H30FA, H39FA, H46FA
Ventilation	Improve air tightness	H37MA
	Closing doors and windows when heating on	H30FA, H37FA
New appliances and systems	More efficient appliances and smart/timed/internet devices	H10MA
	Better standby loads on appliances	H10MA
	Larger drum washing machine so fewer washes per week	H10FA
	More energy efficient devices	H39MA, H46MA
	A rated white goods	H37MA
	Energy recovery systems (condensing boilers)	H10MA
Hot water use	Showers instead of baths	H09FA, H10FA, H39MA
Smart home technology	Improve the heating boiler thermostat	H46MA
	Heating and lighting control from iPhone	H10MA, H37MA
	Better heating controls (zoned)	H37MA

Categories	**Householders' ideas**	**Participant's contribution**
	Provide a display of current energy consumption and comparison with a benchmark	H37MA
	Check accuracy of central heating remote thermostat	H30FA
	Movement sensor to turn on lighting where needed	H30FA
	Motion sensors on lights	H37MA

The most popular set of reduction measures was focus on the use of less electricity by changing current behaviours. Householders identified several measures to reduce electricity consumption, the category ‘use less electricity’ accounts for those achieved by using less energy using goods or by improving the efficiency of their daily practice. Also, a number of households mentioned measures that entailed adding insulation, the replacement of lights by LEDs, and heating occupied rooms. Other less popular measures were: the limitation of ventilation, the limitation of hot water use for showers and baths, stopping using the tumble drier, the replacement of the boiler, sealing the house, replacing doors, switching off additional fridge-freezers and buying appliances with lower standby loads.

7.2.3 The impact of reduction measures

Householders were asked to rank the impact of reduction measures and this turned out to be fairly close to the model results in most cases. They firstly listed insulation measures, then those affecting hot water use and finally small appliances. Nevertheless, there were important discrepancies; for example, H30FA believed that the highest reduction was possible by stopping the use of the tumble dryer; H30FA also ranked the energy reduction from switching off her second fridge higher than turning down the central heating; in H37, FA thought that the impact from minimising ventilation was lower than that from reducing the use of small appliances; in H39 (solid wall house), both participants thought that changing windows was more important than insulating the walls; H39 participants also ranked turning the heating down one degree lower than charging less often media devices; and, in H46, they significantly underestimated the retrofit potential, ranking these measures down the list.

7.2.4 Willingness, barriers and time frame to apply measures

Users' willingness to apply change was considered in order to quantify acceptable reduction measures. The approach taken to evaluate the impact of householders willingness and the assumptions within the model are explained in Section 8. The following terms were used during the interviews:

Willingness:

- Yes: willing to apply a measure,
- Only if: willing to apply change if a condition is met (they only would apply that measure if something else happens, for example a lifestyle change, or the acquisition of an innovation technology),
- no: not willing to change their current situation,
- partially: willing to change it to an extent, but not interested in fully applying the conditions specified,
- partially applied: currently applying the reduction to some extent and not willing to change their current routines, and
- applied: already applied.

Time-frame:

- short term: Willing to apply a measure within the following year;
- near future: measure to be considered within the following 5 years or so; and,
- long term: thinking of changing the current status in at least five years time.

The thematic analysis was performed at a semantic level, where interpretative work was undertaken in order to build on the barriers presented here. During the thematic analysis, themes emerged from the coding of the data, related to participants' barriers towards energy reduction based on their home energy consumption experience. The themes which emerged from the interviews are presented here.

The following barriers to adopting energy measures were identified from the thematic analysis of the participants responses. The barriers mentioned for each measure, the number of times the barrier was identified, and the most common barrier are shown in Table 7.3. The description of the barrier and coding examples are added for illustration:

Comfort: reduction measures impact on basic satisfaction needs perceived by householders. Temperature, humidity and air quality can affect people's physical and psychological feelings, making them feel uncomfortable at specific conditions and therefore leading them to take action against it. Some quoted examples used to show comfort/discomfort feelings are:

'*... but I am not going to worry about the energy consumption at the cost of comfort. OK, so I am not going to say, right, everybody is walking around the house in their swimming shorts, just so you are comfortable because the temperature is at 25, that is not reasonable, but if it is at 19, 20 and the boys need to put a jumper on, then that is fine.'* H10MA

'*... but I don't want the fresh air to come in through a hole, where I can not control it. If I want fresh air, I want to open a window, or a trickle vent. I do not want to just hope I get enough fresh air through a hole.'* H37MA

Everyday life: family lifestyle is limited by a number of constraints such as working patterns, family commitments (for example school and commitment to clubs) and habitual routines in the home, but also preferences and values that shape everyday routines, for example what a family chooses to cook or how they choose to shop. Quoted examples are:

' *The dog comes in and out as he pleases, we leave the door open for him which is maybe not something we should do.'* H05MA

' *I don't think we could turn the fridge off... It is full of food! we have got the allotment, where we have twelve pumpkins! Or however many we've got! And we need to, I tend to make things like soups or we just freeze, you know, we've got that much fruit and veg ... also we buy in bulk as well, we only go shopping once a week, because you work full-time, you haven't got time, have you?; I may as well get three for the price of two, it is cheaper.'* H09FA

Technology: existing technology on the market, does not offer the service expected by householders. This finding supports the position taken in previous studies, which claimed the need to improve CFLs[2] in order to give a similar lighting output to traditional incandescent light bulbs and to be compatible with previous bulbs in order to be accepted by consumers (BSRIA, 2007; Crosbie and Baker, 2010). One householder claimed the development of technology to implement reduction measures in the house:

‘ *Yeah, well I mean we are working our way around with the LED lights, but it is getting the right ones for some of the fittings because you know you just cannot get the right type of lights yet, and you know, oh and particularly when they are sort of candle lights or something like that, it's quite difficult to get. So as they become available, the appropriate ones, then we are replacing them.'* H05MA

Investment: the cost of the intervention is not considered affordable or cost-effective and householders do not consider undertaking the intervention. Quoted examples that elicit this fact are:

‘*... and yes, we could probably do more if we insulated the house more, but at the moment the cost of that is prohibitive because we've got a solid wall house.'* H39FA

‘ *The windows will have to be replaced at some point and there's a couple already nearing the end of their life, so again, depending on cost, we would certainly consider triple-glazing.'* H05MA

Information: either the lack of knowledge about an intervention, its impact on energy reduction and/or investment required to undertake it, or the lack of understanding regarding the impact of a specific measure, can influence people's motivation for change:

‘*... but the other sort of things like, I don't know, the seal around the door and that sort of thing, I don't know how much that costs, I don't know how much that costs.'* H37MA

‘*... and then of course you're reliant on the people who are doing the work, and when I went to them, they said, oh you don't need it quite that thick. And then you think, well actually, would we have benefited if it had been a little bit thicker. And it's that, the data to help you make an informed decision about what to do just wasn't there.'* H39FA

Organisation: fitting in the diary the time for a retrofit, the research needed to ascertain the best investment to reduce energy in the home and make an informed decision to be energy efficient can be non viable for householders. Similarly deciding when to undertake a retrofit measure and how different changes in the home are interrelated and dependent on each other.

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[2] Compact Fluorescent Lamp

'*... we would do at a time when we were doing other work to the house.*' H39FA

'*Its all part of the kitchen refurbishment ..., we need a bigger fridge. So kitchen refurbished, have a big fridge in the kitchen and then do away with that one out there.*' H37MA

Lifespan: replacing a device or applying a retrofit intervention needs an investment of money that householders are only going to make if goods need replacing/updating. Quoted examples are:

'*... and we will go out and buy a more expensive bulb, knowing that it's more energy efficient. But you're only doing it when you have to do it.*' H10MA

'*... we have got devices which are old, like we've had the microwave since we got married, so we know that when that's replaced, we can get a more energy efficient device.*' H39FA

Functionality: acquiring and using equipment for a specific purpose makes it infeasible to change it or stop using it. For example, householders quoted the following:

'*I think functionality comes into it, so you, when you go to buy a media device or white goods, you've got two things you're thinking about, one is the functionality and the other thing is how much is it going to cost me to run.*' H37MA

'*The most important thing is that it meets our needs, it does the washing, the capacity is big enough, and then we will look at energy efficiency relatively low down the priority list I guess.*' H05MA

Aesthetics: the aesthetics of a retrofit or replacement appliance is important for householders:

'*The problems for me are: you're then moving away from a brick façade to a rendered façade.*' H37MA

'*They'll stick blocks on the outside of the house ... And that's going to look ridiculous, that's going to reduce the value of our house.*' H39FA

Disruption: the process involved in retrofit measures is usually disruptive, this being a barrier for householders to undertake a retrofit intervention as the following quote suggests:

'*It's the inconvenience, with the fact that you know we are trying to have our normal life and the children at school, it would be a big disruption.*' H39FA

Table 7.3: Barriers to apply reduction measures.

Measure	**Most common barrier**	**Number of times**	**Other barriers reported by householders**
New media devices	Lifespan and functionality	7	-
Triple glazing	Investment	7	Technology, organisation, information, lifespan
Installing a new boiler	Lifespan	7	Investment
New cooking appliances	Lifespan	6	Functionality organisation and information
New laundry appliances	Lifespan	6	Everyday life
Wall insulation	Investment	6	Technology, disruption, aesthetics, everyday life, information
In use heating	Technology	5	Investment, everyday life, information and comfort
Heating to 17℃	Comfort	5	Technology, investment and everyday life
New fridge-freezer	Lifespan	5	Investment, organisation
Floor insulation	Information	5	Disruption, investment
No tumble drying	Everyday life	4	Functionality
Ventilation	Comfort	4	Everyday life, information, functionality and organisation
Loft insulation	Lifespan	4	Organisation
One fridge-freezer	Everyday life	3	-
No standby loads	Information	3	Everyday life, technology
Replace bulbs	Lifespan and technology	3	Investment and organisation
Sealing	Information and organisation	3	Investment, and everyday life
No heating over 15℃	Information	2	Technology, information, everyday life, organisation, comfort
Heating when home	Everyday life	1	Technology and organisation
Insulated doors	Lifespan	1	Investment and functionality

7.2.5 Lifestyle measures

Householders who own more than one fridge-freezer were not willing to reduce the number of cold-appliances (except for H30), because of householders shopping, cooking and food storing practices, which are part of the everyday life barriers; see Table 7.3. H30FA, stated they would get rid of the second appliance in the near term as it fulfils a 'temporary family need'.

Standby loads were found to have a very low impact on whole house energy consumption. Most householders were previously aware of these loads, although onlyparticipants in H05 and H39 thought about switching them off to reduce energy consumption, and H09 was already using a remote control to reduce them. Participants overestimated the standby reduction potential, and their main reason for not reducing them was to remember to do so on a daily basis, to 'have to switch off appliances manually' and to being uncertain of the benefit of switching them off.

The impact of stopping the tumble dryer was especially high in H46, which is also the biggest family in the sample; in some of the households, H05 and H39, had already stopped using their tumble dryer for different reasons, i.e. liking more the results from drying clothes outside or not considering the tumble dryer necessary or worth using; other householders only use it due to a combination of everyday life constraints and bad weather conditions, and only participants from two households, H30 and H46 were not willing to stop using it; H30 FA, was surprised with the predicted reduction, which was much lower than her previous expectations; and, H46 considered their use of the tumble dryer necessary due to the number of people living in the house and their laundry preferences.

Switching off the heating when no one is at home is considered by most householders as a first priority action, being already partially applied in the homes; most participants reported difficulties in remembering to do it before leaving the house, such as H05 and H37; others do not have the best control tools to program it accurately, as reported by H30FA; and others are occupied most of the time, which is the case for H10 and H46.

Heating occupied rooms instead of central heating the house was a measure already applied in some houses; in H05, H09, H10 and H39 participants eventually use TRVs and wood burners when the whole house does not need heating. Householders expressed their willingness to heat only occupied rooms, but they found it difficult due to the lack of a control system that would ease the implementation, the investment associated with buying new control systems and the lack of information about their benefits. It was found that the assumptions within the model to quantify reductions from heating zones instead of central heating the house were infeasible in reality as most rooms were occupied during the evenings, at least in most family homes, which meant that the modelled reductions for this measure were overestimated. These insights were used to adapt the model to reflect this finding.

The impact of ventilation varies significantly within the sample. During the interview, H05MA reported that most windows were opened for hours on a daily basis, as it was suggested by its high reduction potential. In H10, where the reduction was very low, they reported that windows were only opened to deal with the steam after showers during the heating season, whereas most windows were generally opened in the summer to let the heat out. It was observed that the model results did succeed in representing ventilation routines, that were totally different home to home. Some participants considered fresh air an important enabler of comfort, indispensable for a healthy environment, essential to keep awake, remove ambient odour after sleeping or cooking, and to avoid condensation and damp. For some participants, ventilation systems such as mechanical ventilation would be an alternative to windows opening, depending on the cost of the system and the cost of running it; for other families, these systems were not a possibility, as they like direct fresh air from outside.

Reducing indoor temperature to 17℃ does not always satisfy the minimum thermal comfort requirements of the householders, as generally suggested in thermal comfort studies; specially for houses with elderly people, babies and young children. But also, other issues were reported, for example in H30 and H39 participants have already set their thermostats at 17℃, but the output temperature was usually higher, either due to the thermostat performance or due to the location of the sensor; and participants in H05, H09, H30 and H37 would consider setting lower indoor temperatures if they had a better control system.

The main reported issue relating to switching the heating off when the outdoor temperature is over 15℃, is the lack of information and agreement about the optimal time to switch on/off the space heating during the year. Families reported having trouble deciding when to switch the system on/off because of changing weather conditions in the mid seasons and the lack of specific information about the outdoor air temperature. Some participants expressed their interest in a control system that could either inform them when the outdoor temperature is over their chosen threshold or automatically switch off the heating if the outdoor temperature was higher than their temperature threshold. Other participants, such as H10's householders, are partially applying this measure by setting the space heating to switch off above their chosen indoor temperature, which meant that the system automatically switches off to avoid overheating in the summer.

7.2.6 Replacement options

The replacement of appliances is mainly driven by the end of their lifespan; laundry, cooking and cold appliances are usually replaced when they stop working, although some participants also change or acquire more devices due to improved functionality or aesthetics reasons. Participants are generally interested in buying high efficient appliances, although this criterion does not apply to some media devices such as iPad, computers, laptops or other game consoles in which functionality is the main concern; TVs are the exception, for example in H09, H37 and H46, participants reported thinking about energy efficiency when buying a new TV. The barrier to choosing the most efficient appliance when buying a new one is always cost. Interestingly, it was found that new TVs not only tend to be bigger, but also they were found to be usually supplemented with high quality audio devices, which can upset the potential benefit from using a more efficient TV.

The replacement of the lighting usually takes place when bulbs stop working. The use of LEDs was found to be constrained by the need for specific fittings in H05, H30, and H39. H10 and H46 participants considered investing in the high efficient technology, a strategy towards reducing their energy consumption, especially electricity, due to its increasing cost in the last years.

The replacement of the outside door was less interesting to householders, partially due to the low reduction found in the modelling results. H30 and H39, reported feeling the cold going into the house because of the unsealed door, not having changed it because of the cost involved and because it needs to be organized and prioritized in their agenda. H30FA preferred to seal the existing door, which is more feasible in the short term than buying a new one. In H46 they were interested in changing the door for aesthetic reasons, but most householders would only change it when it needed replacing. In one specific case, H09MA mentioned that the fire door in the back room was generally cold due to its high conductivity, but because it is a fire door, they had not considered replacing/insulating it.

7.2.7 Retrofit opportunities

Retrofit measures entail a high reduction potential, especially for solid wall houses, H30 and H39, especially H30, which has no loft insulation. It was also observed that retrofitting had a big impact in houses with a significant glazing area or/and single glazed windows, such as H09, H37 and H46.

H30FA and H39 adult members, both home owners from solid wall houses, did not consider retrofitting options due to the cost involved. H30FA tried to apply for the Green Deal initiative but did not add external insulation to the house because of the Green Deal constraints, the repercussion of cladding upon the aesthetics of the house and the guarantee of the retrofit, which only covered 20 years, added to the fact that insulation materials were still in development. Householders in insulated cavity houses did not consider improving their insulation levels in the short term, and in the long term they considered it undesirable due to cost, disruption and aesthetics.

Householder interest in insulating the ground floor was generally low. Participants from H39 and H46, which have already applied some floor insulation, did it by adding a carpet to the upper layer of the ground floor. H37MA did not consider it at all, for a number of reasons: disruption, lack of information about the benefits from doing it and the required financial investment.

Householders' interest in triple glazing was higher, but the cost of it was high and it was only considered in the long term, when their current glazing needed replacing. H46 also reported being willing to change them due to aesthetics, whereas H39 has already looked into the cost involved and found it expensive, especially for curved glass solutions.

Overall, participants knew about their unsealed doors and windows and were able to detect specific locations where heat was leaving the house; others like H05MA and both participants in H09, found difficult to locate infiltration paths in the house and were not able to determine whether sealing the house would be cost effective.

The replacement of the boiler was in all cases determined by the end of its lifespan and the investment needed in order to get the most efficient one at the time of change.

7.2.8 Technology as an enabler of energy reduction

Participants suggested technology ideas that they thought would help them to reduce energy consumption in the home. Interestingly, most of the technologies suggested are currently offered on the market, although householders were not aware of this.

Householders generally agreed on the need of better controls to ease the implementation of in use heating, heating when home and no heating over 15℃. H30FA already controlled the heating with a modern remote temperature controller which allows temperature settings at different times and in different locations, but H30FA thought it was now more difficult to switch the whole central heating system off, having to switch off/change temperatures zone by zone:

'what is really annoying about my modern remote thermostat is that my old thermostat had like an override switch on it, I could switch it on, switch it off really easily. This one does not, it is all in zones. So you can switch it off by putting it on the frost 'stat' but that is kind of annoying somehow. So if you are in the house, but you want the temperature lower, you would have to go through manually adjusting all the temperature zones, you cannot just say I want it today, or not easily anyway, to be at this temperature, you would have to re-programme it.' H30FA

There were basic heating control technologies in H37, H39 and H46; the respective participants wanted to have a remote control for management of the radiators instead of going radiator by radiator switching TRVs. H37MA also mentioned his interest on mobile applications to ease the heating control. Basic sensors to control the indoor and outdoor temperature would allow participants to make informed decisions on when to switch on/off the heating and/or to automatically switch the system off above a specific temperature.

Four of the participants mentioned their interest in feedback devices and householders gave different specifications on what information and in which format they would like to receive feedback. H05MA mentioned his interest for a connected device which could be used to see their expenditure, as he has already tried with an in home display and did not find it engaging. Other feedback preferences, included the use of feedback screens to see their instant energy consumption and being able to see cost information at an appliance level. H10 participants were very interested in smart home technology, specifying that they would like to manage everything in the house with a remote control; also, H30FA and H37's family would like to have motion sensors to automatically control lighting.

Some householders would like to control the heating system by turning it off when windows are opened, which was considered by those families who would not change their current opening behaviour, preferring to have lower indoor air temperatures than limiting the opening of windows.

H39FA would like to be offered an insulation material to easily spray on the outside of a solid wall envelope, and H10 FA wanted to remotely control the curtains to reduce/increase sunlight.

Observations from this study suggest that most of the lifestyle reductions were theoretically achievable without the need for automation or smart home technology over and above traditional domestic control methods. Most, however, require ongoing commitment from householders, who need to overcome everyday life, organisation and comfort barriers in order to reduce energy. The opportunities for smart home technology fall within the lifestyle reduction measures where automation and control can empower and encourage householders to make changes to the way they consume energy and can provide convenience. Lifestyle reductions apart from ‘One fridge-freezer’ and stop using the tumble dryer can be enabled through smart home technology using technological solutions that are already commercially available or in the process of being commercialised.

7.2.9 Participant feedback

Participants agreed that their tailored achievable reduction was higher than expected. H09 and H46 said reductions were too optimistic and not viable at a first glance; H05MA and both participants in H10 were not sure if those were possible but they were surprised about how high they were, and H30, H37 and H39 thought they would be viable. H30FA and H39’s participants highlighted that in their case, reductions would only happen if an important investment was made.

H05MA and H09’s participants were surprised about the impact of ventilation, not having previously thought about it and thinking that the impact of opened windows when the heating was on was lower. H09 and H37 were surprised about the low reductions from LED lights and the high ones from triple glazing. H10’s new washing machine was giving lower reductions than they were expecting; and H46FA forecast lower reduction from stopping the use of the tumble drier; H30FA thought that tumble driers were responsible for most energy in the home, over and above central space heating energy consumption, being surprised about the low achievable reduction from stopping it. H37MA, a specialist on air-tightness, thought the infiltration reduction would have a higher impact, and, H46's participants thought that insulating the house would have a lower impact because of a conversation with friends. Generally, participants showed different understandings on the impact of measures, suggesting a broad range of backgrounds and knowledge.

The 'REB' categorisation was discussed with participants to understand if 'REB' added something interesting to the analysis. Most householders discussed the fact that behavioural measures could enable surprisingly high reductions and that did not require an investment:

'*But the biggest things, simple changes isn't it, what you can do yourself, without actually spending money really.!'* H09FA

' *You can see straight away what we can do like instantly.'* H46MA

'*You could get there by either applying half of the behavioural and technological interventions or one of them, the behavioural look more doable.'* H10MA

The graphical information of the potential reductions presented to the participants did not always resulted in a willingness for applying reduction measures but sometimes they led to a change in priorities. For example, H05MA changed his view on the door draught problem, as he had it as a priority to reduce the space heating costs when, in reality, there were constantly open windows around the house:

'I was thinking of replacing the letterbox and changing the front door, but there is no point if I have got all the windows open.' H5MA

H09 said how surprising it was that almost 50% of the potential reduction was based on behavioural change:

'I thought we were very good really and obviously there is still a lot we could do.' H09FA

H30FA also mentioned that behavioural change had a bigger impact than she first thought. H37MA said that the information given during the interview would have changed their decision when they replaced the windows, thinking that triple glazing would not have had that big an impact but now seeing that it would.

Householders were also asked what they missed in the discussion. H10MA wanted to know more about the impact of alternative energy sources and how investment in these would compare with the replacement of appliances and retrofit. H05, H37 and H39' participants agreed the importance of making sure the efficiency rate is the highest on the market when purchasing appliances. H05MA would like to know the right time to replace appliances, as the market is continuously offering improved technology efficiencies. H37 and H39's family members wanted to know actual differences in energy consumption of different appliances and how to find objective information before buying, rather than having to trust companies' marketing.

All householders except H30FA thought it was feasible to get to target reductions, although they still believed that modelled reductions were too high and probably not realistically going to happen due to personal barriers. H30FA did not think it was possible to achieve intended reductions, as they did not consider it a realistic option to improve the wall insulation unless the cost of the implementation and the retrofit process became more convenient and cost-effective not either to apply big changes to their daily life:

' *Not very realistic. I actually think that although I can make some small changes, I think possibly in the short-term there is nothing that is massively significant that I could do. Obviously the loft insulation and I will perhaps start turning things more off at night, standbys. I probably will adjust the timer clock, until it gets colder, to have less time in the morning. But I think in the short-term, I am thinking it is not so much I can do. Yeah I think it is possibly going to be harder to do, quite hard to do.'* H30FA

7.3 Summary

The interviews are designed to enable a personalised discussion with householders around their current energy consumption and on the impact of possible reduction measures, contextualising the study within the 2050 UK target. Graphical information on the impact of applying reduction measures in the house was used to understand their willingness to apply them, leading to a discussion of their barriers and limitations; also, they were asked to suggest potential smart home technologies that could facilitate the application of measures.

Householder interest in reducing energy demand is mainly driven by their willingness to reduce fuel cost. This can be partially attributed to the fact that all of the sample are home owners, the house tenure that are most likely to consider energy-efficient home upgrades as indicated by previous research (Black et al., 1985). Barriers that prevent householders from applying reduction measures reflect previous research, for example the lack of information, lack of trust in information sources or lack of a critical view to make a choice (The Technology Strategy Board, 2013; Lutzenhiser, 1993; Frederick et al., 2002; Wilson and Dowlatabadi, 2007; Karvonen, 2013; Simpson et al., 2016).

Householders' decisions to invest in home improvements and energy efficiency are constrained by their understanding of energy consumption. Also, daily energy consumption can be affected by their understanding, for example, most householders avoid the use of the tumble dryer or invested in LED lights when they have to update the old ones. Nevertheless, the understanding of householders is not enough to enable them to make the most effective decisions concerning energy reduction. For example, householder investment in efficient appliances was not giving them the reduction expected; the opening of windows and doors was unconsciously impacting on their space heating consumption; the use of the central heating was unnecessarily supplying heat to unoccupied rooms or they were not able to decide how to invest their money on retrofit options because they were not sure which one was most cost-effective.

Although participants were generally interested in the uptake of reduction measures, in some cases, comfort and convenience values surpass the benefit from reducing their expenditure. Such measures could be applied by dissipating the comfort and convenience penalty through the use of smart home technology as discussed by householders. The energy impact that smart home technology can have on households' energy consumption is evaluated in Chapter 8.

This chapter achieves Objective 6 in Chapter 1 by assessing householders' willingness to undertake reduction measures and by identifying the barriers that prevent them from applying the changes.

Chapter 8

Likely demand reduction

This chapter brings together the energy demand reduction modelling work with the insights from the interviews. The results from the interviews are transformed into two sets of reduction measures: those that participants would be ready to accept/implement; and those that could be assisted through the application of smart home technology [1]. The reductions model is re-run for each home comparing the findings with the results from the previous model to discuss the impact of acceptable changes and the potential role of smart home technology to achieve the 2050 national domestic energy reduction target.

8.1 The impact of acceptable measures

Willingness to apply measures in the home is a key aspect for the implementation of energy reduction measures (Poortinga et al., 2003). Ultimately, in owner occupied dwellings, it is the householders who make the decision to invest and apply changes to their lifestyle in order to benefit from energy reduction. Results from the interviews reported in Chapter 7 suggests that the response to reduction measures falls into one of three categories: unacceptable, acceptable and acceptable only under specific conditions. The analysis presented here draws a line between what householders are willing to apply in their home, although under specific conditions, and what they do not wish to change.

Each measure in turn was considered for each household and one of six options used to model the response, as is summarised in Table 8.1. If householders were willing to apply a measure without

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[1] Smart home technology enables the user to remotely or automatically control aspects of their home which may include: appliances, lighting, heating, and ventilation systems. User control may be enabled from any location via an internet connected smart-phone, tablet or computer (Time Inc.UK Ltd Technology Network, 2016).

caveat, no change was applied to the model. For those reductions which were only applicable under a condition, the condition was evaluated based on householders' interview comments, tailoring the degree to which the measure could be applied. The assumptions applied in the model were specific to each reduction measure and each household and are explained in detail in the following sections.

Changes that were unacceptable were not implemented in the model. For measures that were applicable, but the modelling assumptions applied in the reduction potential evaluation (Chapter 5) did not represent the conditions found in the home, these were adjusted accordingly.

Table 8.1: Model assumptions based on participants willingness.

Participants willingness	**Assumption in the model**
Willing to apply a measure	Assumptions as modelled before the householder interview
Willing to apply a measure if a condition is met	Condition evaluation; it is applied if the condition is related to policy or other third party intervention
Not willing to apply a measure	The model is corrected to disregard the measure
Willing to partially apply a measure	Reduction assumptions customized in line with the participants willingness
Already partially applying a measure	Measured disregarded
Measure already applied	Measured disregarded

Minimum ventilation

This measure was applied only in those houses that would consider having a ventilation system to minimise their ventilation heat loss. It was applied in H09, H39 and H46 as H05, H10, H30 and H37's participants wanted to keep ventilating their house without a ventilation system; H05, H10, H30 and H37 family members showed their interest in reducing their window opening time but they would apply personal considerations; the impact of that behaviour change was not evaluated because the ventilation rate that householders were willing to apply was not measurable at that stage of this work. Further research could evaluate what would be the output ventilation rate resulting from applying householders' preferences to natural ventilation practices.

Sealing the house

Householders reported to be willing to seal the house if the cost was reasonable and it was not highly disruptive. The assumption applied in the evaluation is that the cost of sealing the house would decrease, becoming a well known cost-effective option. This measure is applied in every house. The infiltration air change rate achieved after applying this measure is different for houses which are assumed to have installed a mechanical system (H09, H39, H46) and those which have not (H05, H10, H30 and H37). The infiltration air change rate resulting from sealing interventions is assumed from a previous publication that reported infiltration air change rates after sealing a retrofitted house, before and after installing a mechanical ventilation system in the Midlands (Hall et al., 2013). This measure has been applied to the model in every house. For houses where MVS was not an accepted option, the infiltration value applied is slightly higher (0.47 ACH) than for those that consider MVS (0.41 ACH) (Hall et al., 2013).

Appliances and boiler renewal

The renewal of appliances and boilers is implemented in all the houses, assuming that the equipment will be renovated at least once before 2050.

Minimum temperature

The minimum temperature applied in the scenario is based on participants reported acceptable comfort levels. The model considers the following:

- households that would accept a minimum temperature of 17℃: H05 and H09's householders;
- households that would accept a minimum temperature of 18℃: H30, H37 and H39's householders;
- households that would accept reducing their current temperature by 1℃: H10's householders; and
- households that would not accept lower temperatures: H46's householders.

Heating when home and in-use heating

All households agreed to consider applying this reduction measure, some with a better space heating control system, some with their current technology. The reduction measure is modelled in every household; for that purpose, a tailored heating temperature and time schedule setting is created for each household based on their occupancy profile. The assumption is that the family occupancy schedule remains as they currently are in the evaluation. This assumption enables the comparison between current energy consumption and energy consumption resulting from applying new heating settings.

No heating over 15℃

All households were interested in applying this measure, so the reduction measure was quantified as explained in Chapter 5.

No tumble drying

This measure was not applied in any house as those households who still were using the tumble dryer, consider their usage to be minimum or not worth changing.

No standby

The reduction of standby loads was considered in H30, H39 and H46 as the other households had either already applied this measure, such as H05 and H09 or were not interested on applying it, such as H10 and H37's participants.

One fridge-freezer

All householders but H30FA needed their current cold storage capacity; this measure was therefore only applied in H30, which was using a second freezer for a temporary need and was willing to switch it off.

Improved insulation

Householders' willingness to improve the house insulation levels vary. Participants were generally uninterested in fully retrofitting the ground floor, but would consider it in the long term. Householders preferred other alternatives in the short term, for example, adding a carpet to the upper ground floor layer. In H37, they stated that they would not consider the insulation of the ground floor at all. Reductions from fully insulating the ground floor were applied to all households except H37, as the evaluation considers long term acceptable changes. It should be noted that there are conditions to implementing this measure in family homes, as solutions should be cost-effective and householders should be better informed about its implications.

Table 8.2 summarises the list of measures that householders considered acceptable ✓, those that were unacceptable x, and those which were accepted but up to a lower degree ✓x. At the bottom of Table 8.2, the reduction achievable after applying acceptable measures is presented.

Table 8.2: Acceptable energy reduction measures.

Reductions (%)	**H05**	**H09**	**H10**	**H30**	**H37**	**H39**	**H46**
Minimum ventilation	x	✓	x	x	x	✓	✓
Sealing the house	✓	✓	✓	✓	✓	✓	✓
Appliances and boiler update	✓	✓	✓	✓	✓	✓	✓
Minimum temperature	✓	✓	✓x	✓x	✓x	✓x	x
Space heating tailored settings	✓	✓	✓	✓	✓	✓	✓
No heating over 15℃	✓	✓	✓	✓	✓	✓	✓
No tumble drying	x	x	x	x	x	x	x
No standby	x	x	x	✓	x	✓	✓
One fridge-freezer	x	x	x	✓	x	x	x
Improved insulation	✓	✓	✓	✓	✓x	✓	✓
Whole house current usage (KWh)	87.8	56.7	88.0	91.8	60.8	79.1	100.9
Acceptable measures usage (KWh)	48.3	27.8	41.4	43.2	32.8	26.9	42.4
All measures usage (KWh)	20.0	14.9	28.9	24.3	20.6	14.7	25.7

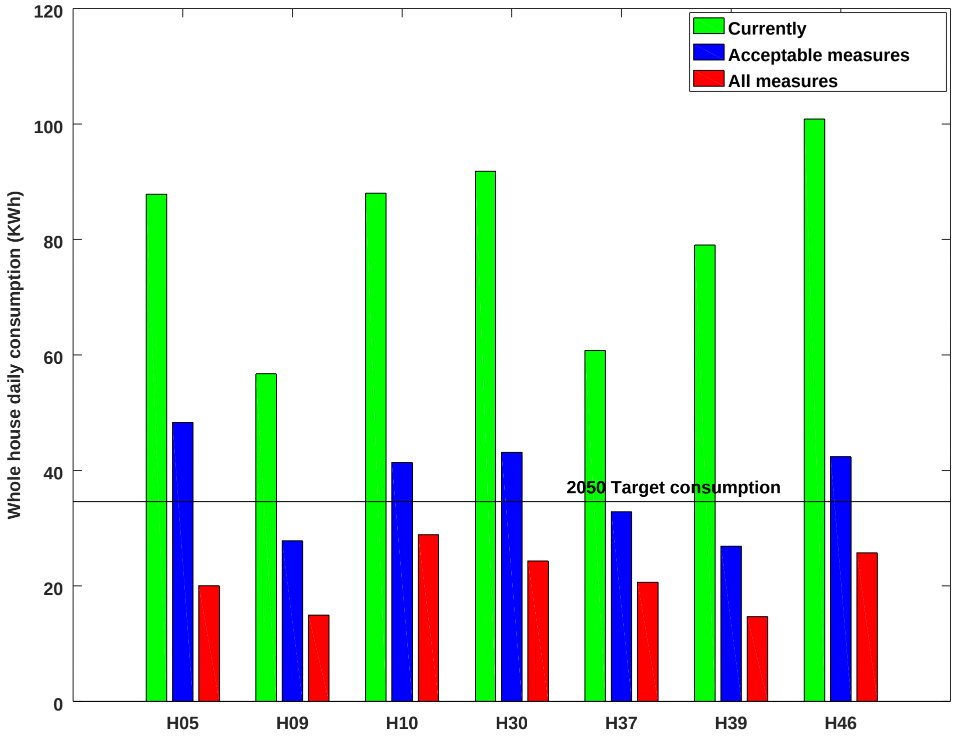


Figure 8.1: Energy reduction potential from acceptable measures, current energy consumption and modelled potential.

To analyse the impact of measures that were not accepted by householders, total reductions from the initial model were compared with those achieved after applying accepted measures in the long term. The impact on energy reduction ranges depended on the number of unacceptable measures and the relevance of those with respect to energy consumption, which depends on each household's specific energy use. The difference in the results varies from 14% in H10 to 32% in H05 as can be seen in Figure 8.1. The difference between the total potential reduction and the reduction from applying measures accepted by householders is in average 20% within the sample. In H05, H10, H30 and H46 the reduction achieved after considering householders' willingness to apply measures would not meet the 2050 target. The qualitative insights suggested that the barriers that result in unacceptable measures are: comfort, everyday life, functionality and information. The lowest acceptable levels of comfort and convenience varies; for example, H05 and H37's participants were less concerned about colder temperatures in the home, whereas current ventilation routines were not negotiable. Everyday life limitations are specific to each household and they are valid for that specific moment in time, as most everyday life barriers are shaped by working schedules, the age of family members, and the use of spaces in the home. For example, H10, H30 and H46 were normally occupied during the day by one member of the family, who was either unemployed, a housekeeper or retired. Also, functionality is a barrier when changing a device or a system, as in some cases the function and the performance of the existing device and the new efficient one was different, this being the reason to keep the old one or buy another that has similar rather than reduced energy rates. This was the case for retaining existing media devices, gas fired hobs, or for not considering a ventilation system. Lack of information was a barrier to undertaking specific reduction measures, in cases where the performance benefit, the cost of the process involved, and the reduction potential were not clear.

Although the impact evaluation of acceptable measures is limited by the assumptions within the scenario set within the model, further scenarios could be envisaged by looking at the interview responses. For example, the impact of acceptable reduction measures could be evaluated if there was no change in the cost of retrofit and replacement.

8.2 Energy reduction enabled by smart home technology

Here, in an evaluation of the proportion of the reduction that might be enabled or facilitated by smart home technology, measures were modelled based on participants' insights. The model evaluates the impact of smart home technology by evaluating those measures that could be achieved through the use of smart home technology and that would reduce energy waste while maintaining householders' personal convenience and comfort levels.

Householders suggested that control automation can result in the reduction of wasted energy that would be practically impossible otherwise: optimal starting of heating in response to patterns of occupancy is one such example. Smart home technology could provide the user with a more intuitive and convenient means of setting critical set-points and parameters, and so makes actioning desired changes more achievable.

Observations from this study suggest that most of the lifestyle reductions were actually achievable without the need for automation or smart home technology over and above traditional domestic control methods. Most, however, require ongoing commitment from householders. The opportunities for smart home technology fall within the lifestyle reduction measures where automation and control can empower and encourage householders to make changes to the way they consume energy and provide convenience.

All of the lifestyle reductions apart from one fridge-freezer and minimizing use of the tumble dryer can be enabled through smart home technology using technological solutions that are already commercially available or in the process of being commercialised. Table 8.3 lists those measures applied in the model, describing the assumptions on how smart home technology might enable the implementation of the reduction measures.

Table 8.3: Reduction measures enabled by smart home technology

Description	**smart home technology application**
No standby loads	Appliances can be turned off manually, however, remote access to switching or implementing algorithms that learn behaviour using smart home technology increases the likelihood of unused appliances being turned off, hence reducing unwanted energy consumption.
Heating when home	The central heating can be controlled manually, but it is much more likely to be effectively implemented if smart thermostats control the heating based on the household occupancy.
In use heating	Smart thermostat systems enable the user control of the heat display in individual rooms by installing wireless thermostatic radiator valves (TRV) or separate thermostats.
No heating over 15℃	Automated control scheduling is not possible with participants current systems but smart thermostats enable the systems automation response to key factors such as outdoor air temperature and humidity.
Ventilation	The application of a MVS could automate the house ventilation to minimise the heat output while ensuring the minimum air change rate.

In the analysis is it assumed that measures certain households would not implement before because of everyday life patterns can be enabled by the automation and remote control that smart home technology offers. The assumption is that smart home technology will remove the need for householders to change everyday life patterns that are non-negotiable or difficult to change. The application of these measures enabled by smart home technology results in a high reduction, enough to reach 35% energy reduction in the sample of households. The potential reduction would be enough to reach 2050 targets in H09 and very near to achieving H37's energy targets as is shown in Figure 8.2. Results from the reduction analysis suggest that smart home technology could provide important reductions, as high as 45% of the energy consumption in H05 and just over 20% in H39. Its impact on energy consumption would be higher than any other reduction measure on its own, as the highest reduction possible is from wall insulation, which could reduce 21% of the energy consumption within the sample and which needs a higher investment and will result in a higher level of disruption. The implementation of smart home technology on its own is not enough to reach 2050 target consumption but can have an important role to diminish the inconvenience that lifestyle reduction measures entail, resulting in higher energy reductions. The effectiveness of smart home technologies does vary between houses. Smart home technologies do not impact on the house state, the user temperature preferences and the household occupancy (number of hours when the house is occupied and number of rooms occupied). Therefore, in order to target the most suitable set of households where smart home technology can achieve a significant reduction, the house state, householders' consumption patterns and willingness of change are key to determine the success of the new smart home technology. There are willingness barriers that householders need to overcome in order to choose and implement smart home technologies. For example, householders were concerned about the investment needed to acquire the new technology, the need to learn which option suits them best and how to use it. They were also reluctant to change current systems which still work and concerned about the aesthetics of the new technology.

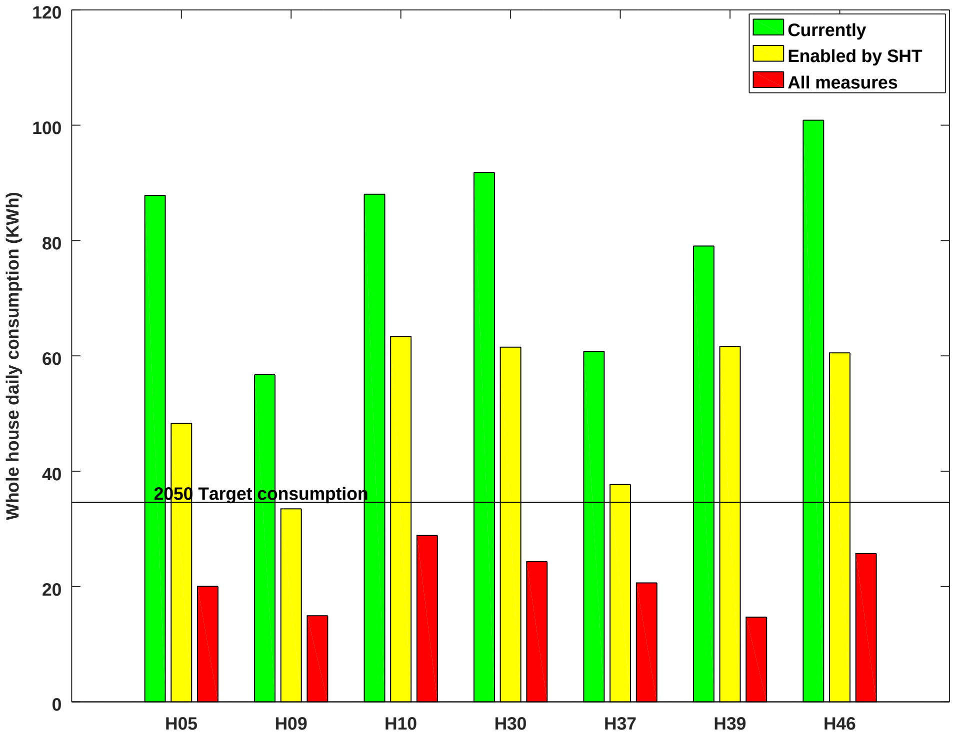


Figure 8.2: Energy reduction enabled by Smart home technology (SHT), current energy consumption and modelled potential.

8.3 Summary

The impact of householders' willingness to implement reduction measures in the long term was quantified by modelling acceptable measures for each house in the sample. It should be noted that a number of conditions must be met for the reductions to be implemented, which are linked to cost, family everyday life, the spread of smart home technology and the lifespan of appliances.

Results suggest that while ensuring minimum comfort expectations and other personal considerations, the reduction required to achieve 2050 UK domestic targets can be achieved in the group of houses, although it is not achieved in all cases. In H09, H37 and H39 users could apply their personal preferences regarding the application of reduction measures and still achieve the 2050 target. In H05, H10, H30 and H46 the target would not be accomplished unless participants change their attitudes towards what they are prepared to change, especially regarding ventilation routines, which heavily impact on energy consumption. Also, a key barrier for further reduction measures is the occupancy during the week, as H10, H30 and H46 are occupied full time during weekdays and unless the occupancy changes space heating will be required at least in occupied rooms during the day.

The achievement of reduction measures will require the design of decision support services that help households assess the potential energy demand reductions and cost savings achievable through investment in retrofit, smart home technology and new appliances in relation to not only the performance of their individual house, but in relation to their own lifestyle choices and the potential to enhance comfort and convenience through the targeted application of smart home technology solutions. The prognosis for the usefulness of smart technology is strong if smart home technology can help mitigate the loss of comfort and inconvenience that comes with implementing lifestyle changes.

This chapter attains the Objective 7 set in Chapter 1 by quantifying the influence of householder's attitudes and preferences to reduce energy consumption, feeding back insights elicited from the interviews to gain a more realistic sense of the 'likely' level or reductions that can be expected in family homes.

Chapter 9

Discussion, conclusions and future work

A socio-technical evaluation of domestic energy reduction measures enables the evaluation of possible implementation measures in domestic dwellings and their likely impact on household consumption, which will be influenced by user lifestyles, routines, preferences and technical characteristics of the dwelling (Summerfield et al., 2007; Boait et al., 2012; Gram-Hanssen, 2010; Santin, 2011; Santin et al., 2009; Guerra-Santin and Itard, 2010; Shipworth et al., 2010). The promotion of home energy efficiency measures has had a lower impact than predicted, partly because of the reported rebound effect (Coleman et al., 2012; Khazzoom, 1989; Greening et al., 2000; Galvin, 2014), and partly because of the assumptions within the evaluation tools (Hens et al., 2010; Kane et al., 2015). Ineffective evaluations of the impact from reduction measures have previously led to lower actual reductions than modelled predictions, for example the output reduction that UK domestic dwellings achieved from installing space heating controls due to the poor interaction between householders and the control tools (Heating and Hot Water Taskforce, 2010). Previous studies have raised the need for monitoring data to inform current modelling tools and for holistic evaluation tools that embrace the complexity of energy consumption in the home (Hazas et al., 2011; Lomas, 2010; Kane et al., 2015; Hong et al., 2006). Although the use of mixed-methods has been used within building research to assess domestic energy reduction, for example the model developed by Lopes et al. (Lopes et al., 2016), the analysis was limited by the lack of monitoring data and household characteristics, assuming relevant parameters for energy consumption such as ventilation rates, the ownership of cold appliances devices, the use of computer and audio-visual equipment or the frequency of use of appliances such as the dishwasher, the washing machine and the tumble dryer; also limited by simultaneously modelling a mix of technical and behavioural measures. Models have been used to estimate energy savings, CO_2 emissions and cost efficiency of the different reduction measures (Johnston et al., 2005; Shorrock et al., 2005). But the output results are hypothetical, based on many assumptions to characterise energy usage patterns in the dwelling and, furthermore, they lack householders' input and validation, regardless of the evidence from previous work that claimed that lack of householders' interest can affect the reduction potential from technical solutions (Haines and Mitchell, 2014).

This thesis explored a method for addressing these challenges in order to promote the tailored assessment of the energy reduction potential in domestic dwellings, and discussed the following issues:

- the characterisation of ventilation heat loss;
- the impact of energy reduction measures on householders energy consumption; and,
- the impact of householders' willingness to apply reduction measures and the potential role of smart home technology.

The characterisation of ventilation heat loss

The lack of monitoring data has led in previous studies to applying rough assumptions on the characteristic of domestic energy consumption, especially on the characterisation of ventilation heat loss. The use of well-known steady-state energy balance principles combined with whole house monitoring data over a 12 month period has demonstrated that it is possible to generate representative estimates for ventilation/infiltration rates, at least during the space heating season. The output daily ventilation rate that represents the heat exchange through infiltration and natural ventilation vary within the sample between 0.5 Air Changes per Hour (ACH) and 2.6 ACH as shown in Table 4.9, Chapter 4. These figures are within the range of previous published values (Energy Saving Trust, 2014a; Bedford et al., 1943; Fabi et al., 2012) and although the approach is limited by the simplifications made in the analysis and the number of uncertain parameters, which are determined by applying assumptions and simplifications to the calculation, the model results suggest that the application of the output household models developed here give plausible figures. The model demonstrated value to estimate gas consumption based on the output ventilation rates (Cosar-Jorda and Buswell, 2015). The ventilation rates are within the range of previous findings and they represent quantitatively the case for the ventilation routines reported by the participants. Nevertheless, the approach should be further evaluated for different applications. With the proliferation of smart metering, this approach could be scaled up to generate feedback to householders on the energy penalty of their ventilation behaviour, and could potentially be used as the basis to carry out more extensive analysis of the impact of ventilation practices on energy use.

The impact of energy reduction measures on householders energy consumption

Although previous studies have evaluated the energy reduction potential from reduction measures, these evaluations have been criticised due to the lack of data used in the models, with results based on poor assumptions about householders patterns of energy consumption. For example, retrofit measures have been claimed for reductions up to 64% of the base energy consumption (Banfill et al., 2011b), and 68% in a Swedish study (Mata et al., 2010), but results are limited to pre-set characteristics of energy consumption that can overstate the real potential, which is influenced by natural ventilation and space heating related usage patterns as suggested in Chapter 6. Although other studies tried to quantify the impact of measures that imply a behavioural change suggesting reductions between 21% and 88%, these were limited by the lack of monitored data and the over reliance on assumptions within the modelling tools and survey data (Ben and Steemers, 2014; Zhou et al., 2008; Martinaitis et al., 2015). Energy consumption patterns affect the potential energy impact from reduction measures, resulting in different reductions for each household, which also affects the priority of energy reductions to be implemented in the home. Real data can be especially relevant for the assessment of energy reduction in households and very importantly to characterise the energy reductions that might be expected from ventilation and sealing measures, as user behaviour is a key parameter to the output space heating energy consumption (Lomas, 2010). Results from the analysis supports previous research that affirms the energy penalty that energy behaviours entail, not only suggesting a potential reduction between 30% and 1% depending on patterns of windows opening, but also finding that these practices are not negotiable for some householders, as they heavily impact on comfort feelings, questioning if mechanical ventilation will be an attractive option to householders regardless of its proven potential to reduce energy consumption (Banfill et al., 2011b; Crosbie and Baker, 2010). This socio-technical analysis suggests that one size fits all solutions can lead to ineffective and costly policy decisions, whereas the impact of changes in householders' lifestyle might have a critical role, having been so far overlooked in policy decisions.

Householders' willingness to apply reduction measures

Although the initial analysis, supporting previous findings, suggests an optimistic view of 2050 due to the energy reduction possibilities, the results do not consider whether householders are willing both to implement change to their current behaviour and to invest in retrofit options and new technologies (Haines and Mitchell, 2014).

Insights from the interviews suggest that householders are willing to apply changes to their energy consumption to reduce fuel cost, but this is not always enough to reach 2050 targets; a number of barriers still need to be overcome, especially regarding the cost of retrofit measures, the lack of information on the benefits involved in applying measures, and the lack of trust in information sources. Householders' understanding of the benefits from applying lifestyle and technology measures and the value of comfort and convenience is often a barrier to change current consumption. These insights support previous studies that identify barriers to implement reduction measures, highlighting barriers such as the lack of information, lack of trust in information sources or lack of a critical view to make a choice (The Technology Strategy Board, 2013; Lutzenhiser, 1993; Frederick et al., 2002; Wilson and Dowlatabadi, 2007; Karvonen, 2013; Simpson et al., 2016). Measures that are acceptable to householders while ensuring minimum comfort expectations and other personal considerations, can achieve 2050 UK domestic targets in many cases but not in others. It was observed that ventilation routines are not always negotiable, despite the energy penalty associated. Also, a key barrier to achieving reduction measures was the observed full time occupancy during the week in many of the households. This should be considered in future evaluations as a potential trend that can stop further household energy reductions, given the relevance of household occupancy for energy consumption (Richardson et al., 2010). But the challenge is even more complex when tailored to each household, as family lifestyle is constrained by the specific context for each household and it is applicable only for a specific moment in time, changing with working schedules, the age of family members, and the use of spaces in the home.

Smart home technology might have an important role as an enabler of domestic reduction measures that involve a behaviour change or a decrease in service, helping to minimise the comfort penalty, thus eventually facilitating the energy reduction process. The reduction that can be achieved through an energy efficient use of smart home technology has been quantified, suggesting reductions ranging from 20% to 45%, enough in many cases to achieve 2050 energy consumption figures. These figures are speculative but can be used as a quantitative reference of the potential that can be expected, supporting previous studies that indicate the potential relevance of smart home technology as a means to decrease domestic energy consumption (Allcott, 2011; Ayres et al., 2012; Nolan et al., 2008; Bittle et al., 1979; Brandon and Lewis, 1999; Darby, 2010).

The achievement of reduction measures will require the design of decision support services that help households assess the potential energy demand reductions and cost savings achievable through changes in current behaviour, investment in retrofit, smart home technology and new appliances in relation to not only the performance of their individual house, but in relation to their own lifestyle choices and the potential to enhance comfort and convenience through the targeted application of smart home technology solutions.

Summary

The socio-technical framework developed in this thesis demonstrates the value of quantifying and examining the impact of energy reduction measures in family homes, characterising the dwellings energy consumption by using monitoring data, and evaluating the impact of reduction measures for each case study based on the household characteristics, the patterns of energy consumption and lifestyle preferences. Although the method uses a large amount of monitoring data and face to face interviews, it could be simplified in order to be used as a tool which could facilitate the evaluation and decision making for assessing the potential from domestic investments and behavioural changes and could, in principle, be adopted widely in the community.

9.1 Conclusions

The conclusions from this research are chapter specific and have been summarised as follows:

1. **Reduction measures are an important part of de-carbonising the domestic sector,** but these can only occur through choices made by the home owner. The energy reduction options are varied and well known but their impact on real house energy consumption, and on householders' way of living, has so far been limited due to the minimal input of occupant behaviour data in energy modelling, this being mostly embraced by social studies, which in turn, lack in-depth quantitative analysis (Chapter 2) ;
2. **A socio-technical framework has been developed** to quantify and examine the

impact of energy reduction measures in family homes by using steady state modelling calculations and monitoring data in combination with a thematic analysis of interviews regarding willingness to undertake measures; qualitative insights are fed back into the model to quantify the impact of acceptable measures. The originality of this approach lies in the explicit linkage of outcomes from the modelling of dwelling energy reducing measures with the attitudes of householders to those measures as applied to their homes. This opens up the possibility of producing a tool which could facilitate the evaluation and decision-making for domestic retrofits and which could, in principle, be adopted widely in the community (Chapter 3);

3. **The use of well known steady-state energy balance principles combined with whole house monitoring data** over a 12 month period has demonstrated that it is possible to generate representative estimates for ventilation/infiltration rates, at least during the space heating season. With the proliferation of smart home technology, this approach could be scaled up to generate feedback to householders on the energy penalty of their ventilation behaviour, and could potentially be used as the basis to carry out more extensive analysis of the impact of ventilation practices on energy use (Chapter 4);

4. **A whole house energy reduction model** is developed, introducing a new framework, the ‘REB’ method, which has been demonstrated in a sample of houses. As smart meters enter the market, the method can be applied to inform home owners about the energy reduction possibilities, their impact on energy consumption and the action required, either through lifestyle changes or investment. The method could also be applied on a larger scale to inform policy makers about the reduction needed from real homes to achieve the 2050 targets (Chapter 5);

5. **The reduction potential from sample family homes** varies as a result of current consumption patterns which are determined by household characteristics, lifestyle choices and personal constraints, especially for retrofit and lifestyle measures. The analysis suggests that the potential reduction from the replacement of devices are less important to delivering energy reduction in relation to 2050 targets. The drivers of action that carry energy implications are specific to each household and can only be examined at the household level, evaluating the different motivations and pathways to achieving energy reductions. Overly simplified assumptions in retrofitting studies applied to one size fits all solutions can therefore lead to ineffective and costly policy decisions, whereas the impact of changes in householders’ lifestyle might be overlooked in policy decisions, especially for ventilation

practices, regardless of energy impact (Chapter 6);

6. **Householders are willing to apply changes to their energy consumption to reduce fuel cost;** but a number of barriers still need to be overcome, especially regarding the cost of retrofit measures, the lack of information on the benefits involved and the lack of trust from information sources. Householders' understanding of the benefits from applying lifestyle and technology measures and the value of comfort and convenience is often a barrier to changing current consumption. Smart home technology is attractive to householders and can enable the application of lifestyle measures minimising the decrease in comfort, thus eventually facilitating the energy reduction process (Chapter 7);

7. **Changes that are acceptable to householders are sufficient to meet 2050 targets in some houses but not in others,** highlighting the importance of the householder for the achievement of targets. The assessment of the impact of ventilation practices on energy consumption and the users' preferences towards ventilation need to be targeted in energy reduction studies given their impact on achieved energy reductions. Also, house occupancy during the week will impact on the minimum energy needed to supply services to the household and so this trend can be a barrier towards further reductions. The prognosis for the role of smart technology is strong as a mean to mitigate the comfort and inconvenience penalty that comes with implementing lifestyle changes (Chapter 8).

Implications

A new application to the commonly used steady-state heat balance method, which is well known for the calculation of energy consumption in dwellings, is used to estimate tailored energy reduction in the sample of dwellings. The approach calculates the energy consumption from monitored data and assigns the daily house ventilation to the residual from the heat balance; the heat balance is used to recalculate the energy consumption after modelling the application of reduction measures, and results are specific to each household. Although the uncertainty of the approach is high given the uncertainty of the input data, which propagates through the equations, and due to the simplicity of the approach, it has been shown to be able to predict plausible ventilation rates during the heating season, and successfully calculate the impact of reduction measures. The model was validated qualitatively, being found to represent differences between people reported routines, monitored data and modelled reductions. The approach needs to be improved if it is going to be used as a tool to estimate ventilation rates alone, given the uncertainty within the calculation, but the method has been shown to be reliable with respect to calculating energy reduction during the heating season, being more realistic than the results from existing modelling tools, which rely on assumed ventilation parameters (Hong et al., 2006; Kane et al., 2015).

The use of monitoring data together with the heat balance approach, enables a tailored analysis framework approach to be used to evaluate the impact that reduction measures might have in real family homes. Although its use for other purposes will need further work to validate the approach, this method can be used to tailor predictions on the impact of energy reduction measures, where modelling has so far been based on assumptions that heavily impact upon the calculations, especially those regarding occupant behaviour, such as indoor temperature choice, ventilation routines or the use of appliances, having been criticized due to their unrealistic results (Lopes et al., 2016).

Building energy research studies recognise the need for more realistic modelling tools that are capable of simulating energy consumption for different household's energy use. This is of special relevance for the evaluation of energy reduction measures, as studies have shown big differences between predicted and real energy savings. The challenge of making realistic evaluations of energy reduction is incremented by the fact that technological modifications to housing that reduce carbon emissions do not guarantee that savings will be achieved in practice due to the tendency for higher comfort levels in the home (Banfill and Peacock, 2007).

This socio-technical methodology is used to develop a model that can evaluate the impact of tailored energy reduction measures and that can implement user willingness as part of the reduction evaluation. The approach is used to study the impact of smart home technology and the impact of participants' acceptable measures in the long term, taking an optimistic view of the 2050 landscape, but could in the future be used to analyse other time-frames and other scenarios, for example, to evaluate how much reduction would be possible if no financial schemes are provided to enable householders' implementation of higher insulation levels. The application of this socio-technical approach on a big scale is expensive due to the monitoring data needed in order to tailor the analysis to each specific household. It is also time consuming, as data needs to be processed to assess householders' willingness to adopt measures and then, feed back the modified set of measures into the model. Nevertheless, as cheaper smart meters enter the market, the cost of the processing will be reduced, and the approach can be developed to reduce the time needed for the evaluation by, for example, replacing interviews by on-line surveys to make viable the approach on a bigger scale.

Results support previous studies regarding the relevance that ventilation has in energy consumption, suggesting that important savings can be made via the implementation of better ventilation routines (Kvisgaard and Collet, 1990; Fabi et al., 2012; Robson, 2011; Martinaitis et al., 2015). Changes in ventilation routines were found to be unacceptable for participants who frequently open doors and windows, partially because they believe that opening to a lower degree or installing a mechanical ventilation system would not accomplish their comfort and health needs for fresh air. In order to achieve reduction measures from ventilation, householders need to gain more understanding of the air conditions in the home and other ways to accomplish minimum health standards.

Although the implementation of control systems to command the space heating did not achieve the expected reductions claimed by previous research (Shipworth et al., 2010), this issue was linked to the fact that providing households with appropriate IT and heating controls needs to be combined with information and motivation to take stronger action with regards to space heating management (Shipworth et al., 2010; Meyers et al., 2010; Hargreaves et al., 2010).

The one clear message from the results is that there is no 'one size fits all' solution that can be applied in households; therefore, tailored assessment is needed to ensure the success of reduction measures, which could be determined by three important variables: current patterns of energy consumption, participants' willingness to implement specific reductions, and the cost associated with the reduction measure.

Policy recommendations

The main reason for householders aiming to reduce their energy consumption was cost, which was unanimous across the participants. To encourage householders to invest in building retrofit and highly efficient systems, smart home technology and appliances, it is important to provide them with cost-effective options in the short term, with clear messages of the benefits they will gain from their investment. The development of policies to support investment in energy reduction measures is therefore crucial if the modelled reductions are to be achieved, as well as provision of information from independent sources supplying personalised feedback on possible reductions, payback times and available financial assistance.

Householders' understanding of energy consumption and the efficient use of systems and devices in the home varied considerably. Overall, householders' understanding of energy consumption and the impact of their actions and the building characteristics, was not enough to enable them to make the best decisions concerning energy demand reduction, either on a daily basis or when making retrofit decisions. This lack of information influenced their decision making by choosing to invest in appliances that gave lower reductions in energy use than expected; opening windows and doors when the heating is on with no consciousness of the magnitude of heat loss; using the central heating even if most rooms are not occupied or not being able to prioritize the best reduction measure because the benefit was not clear. Interestingly, the feedback on possible savings does not always lead people to wish to apply a change. In some cases, the value of comfort is higher than the possible financial benefit from applying a specific measure. Such reductions in comfort in the near future could be dissipated using smart home technology, which can automate user actions and reduce energy waste. Uptake of such smart technologies could be more strongly promoted in relation to energy demand reduction so that householders are more aware of the available technologies, the potential benefits in terms of convenient energy demand reduction and how to use them to make the most of their investment.

9.2 Future work

This research has developed a framework to quantify whole house energy reduction measures in specific homes, giving insights into the impact from reduction measures in sample family homes and the willingness of households to undertake these. The approach can be developed by:

- evaluating further reduction measures that apply to the use of hot water and end use appliances;
- improving the modelling approach for the calculation of the ventilation heat loss by reducing its uncertainty;
- validating the output ventilation rate with physical testing (pressure testing or similar);
- looking at different 2050 possible scenarios, deducing householders' unacceptable changes under different situations and calculating consequent reductions;
- adding to the assessment tool an estimation of the cost and the payback factor for each reduction measure; and,
- applying the socio-technical method to a bigger sample, considering a variety of households, in order to untangle which measures are interesting to householders.

9.3 Final remarks

This thesis has evaluated the energy reduction potential from a set of reduction measures in a sample of family homes located in Loughborough, in the East Midlands of the UK, considering both technical and behavioural aspects of energy reduction. The approach combines quantitative and qualitative techniques to assess the impact of reduction measures upon energy consumption and householders' current lifestyle. A whole house model was developed to estimate tailored reductions using monitoring data, house measurements and self reported survey answers. Reductions were associated with retrofit measures, replacement of appliances and lifestyle measures, quantifying their potential and framing a 'Reduction Effort Balance' based on the actions required by householders. These results and the total energy reduction were compared to a 2050 target figure and presented to householders to qualify the approach; semi-structure interviews enabled the comprehension of householders' willingness to apply measures, their personal barriers and their 'unacceptable changes'. The quantitative impact of unacceptable changes was analysed by modelling a 2050 scenario where energy reduction measures were applied except for each household's set of unacceptable measures, driving the focus of the reduction potential evaluation towards the behavioural aspect of the challenge.

The output from the socio-technical approach feeds into three different areas of research: it supports previous modelling studies by trying to incorporate complex behavioural dimensions by developing a quantitative model which is based on tailored monitored data and which evaluates the impact of both behavioural and technical reduction measures, validating the model assumptions with householders, and applying users' unacceptable measures to the model. This results in a people-centred evaluation modelling tool that can be used to assess households specific energy reduction potential as smart meters enter the market. The approach uses a well known steady-state energy balance to assess ventilation heat loss; results generated air change rates within the range of those found in the literature; these estimates were found to capture, at least qualitatively, ventilation routines in dwellings. Finally, results contribute to the on-going debate regarding the effectiveness of intervention measures, providing insights relating to which barriers need to be overcome to achieve reduction measures and speculation on how smart home technology might help to decrease energy consumption.

Tailored information is crucial to determining which reduction measures are effective in the home. Evaluations should be based not only on building characteristics but on user patterns of energy consumption, uncovering user practices that have an energy penalty.

The impact of energy reduction measures can be quantified by monitoring whole house energy consumption with enough detail to model the ventilation parameter and to identify end use consumption. Data can be supplied by smart home technology, which at the same time offers a control system to householders, easing the implementation of lifestyle measures.

Smart home technology can therefore enable the achievement of meaningful information for householders that can also be used in energy reduction evaluations, being at the same time a tool for householders to ease the impact upon comfort from applying lifestyle measures. The method presented here can be used in combination with smart home technology to supply tailored information to householders and to inform policy makers regarding realistic assessment of the impact of energy reduction measures upon domestic energy consumption.

References

Abrahamse, W., L. Steg, C. Vlek, and T. Rothengatter (2005). A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology 25*(3), 273–291.

Allcott, H. (2011). Social norms and energy conservation. *Journal of Public Economics 95*(9), 1082–1095.

Amaratunga, D., D. Baldry, M. Sarshar, and R. Newton (2002). Quantitative and qualitative research in the built environment: application of mixed research approach. *Work study 51*(1), 17–31.

ASHRAE (2001). Fundamentals handbook, non residential cooling and heating load calculation procedures. *Atlanta, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers*.

Ayres, I., S. Raseman, and A. Shih (2012). Evidence from two large field experiments that peer comparison feedback can reduce residential energy usage. *Journal of Law, Economics, and Organization*, ews020.

Baker, P. (2011). Historic scotland technical paper 10. Technical report.

Banfill, P. and A. Peacock (2007). Energy-efficient new housing the UK reaches for sustainability. *Building Research & Information 35*(4), 426–436.

Banfill, P. F., S. Simpson, M. C. Gillott, and J. White (2011a). The potential for energy saving in existing solid wall dwellings through mechanical ventilation and heat recovery. *European Council for an Energy Efficient Economy, summer study*, 6–031.

Banfill, P. F., S. A. Simpson, M. C. Gillott, and J. White (2011b). Mechanical ventilation and heat recovery for low carbon retrofitting in dwellings. In *World Renewable Energy Congress-Sweden; 8-13 May; 2011; Linköping; Sweden*, Number 057, pp. 1102–1109. Linköping University Electronic Press.

Barbu, A.-D., N. Griffiths, and G. Morton (2013). *Achieving energy efficiency through behaviour change: what does it take?* Publications Office.

Baxter, L. W., S. L. Feldman, A. P. Schinnar, and R. M. Wirtshafter (1986, 4). An efficiency analysis of household energy use. *Energy Economics 8*(2), 62–73. ID: 45.

Beaumont, A. (2007). Hard to treat homes in england.

Becker, L. J. (1978). Joint effect of feedback and goal setting on performance: A field study of residential energy conservation. *Journal of applied psychology 63*(4), 428.

Bedford, T., C. Warner, and F. Chrenko (1943). Observations on the natural ventilation of dwellings. *J Royal Inst Br Arch*.

Behavioural Insights Team (2011). Behaviour change and energy use. *Cabinet Office, London(available at)/http://www.cabinetoffice.gov.uk/resourcelibrary/behaviour-change-and-energy-useS*.

Bek, G., J. Toftum, and G. Clausen (2011, 11). Modeling ventilation rates in bedrooms based on building characteristics and occupant behavior. *Building and Environment 46*(11), 2230–2237.

Ben, H. and K. Steemers (2014, 9). Energy retrofit and occupant behaviour in protected housing: A case study of the brunswick centre in london. *Energy and Buildings 80*, 120–130.

Beng, D. J. (2003). *A physically-based energy and carbon dioxide emission model of the UK housing stock.*

Birdsall, B., W. Buhl, K. Ellington, A. Erdem, and F. Winkelmann (1990). Overview of the doe-2 building energy analysis program.

Bittle, R. G., R. Valesano, and G. Thaler (1979). The effects of daily cost feedback on residential electricity consumption. *Behavior Modification 3*(2), 187–202.

Black, J. S., P. C. Stern, and J. T. Elworth (1985). Personal and contextual influences on househould energy adaptations. *Journal of applied psychology 70*(1), 3.

Boait, P. J., D. Dixon, D. Fan, and A. Stafford (2012, 11). Production efficiency of hot water for domestic use. *Energy and Buildings 54*(0), 160–168.

Boardman, B. (2007). Home truths: A low-carbon strategy to reduce UK housing emissions by 80% by 2050. Technical report.

Boardman, B. and S. Darby (2000). *Effective Advice: energy efficiency and the disadvantaged.* Environmental Change Institute, University of Oxford.

Boardman, B., S. Darby, G. Killip, M. Hinnells, C. N. Jardine, J. Palmer, G. Sinden, K. Lane, R. Layberry, and A. Wright (2005). 40% house.

Bourgeois, D., C. Reinhart, and I. Macdonald (2006, 7). Adding advanced behavioural models in whole building energy simulation: A study on the total energy impact of manual and automated lighting control. *Energy and Buildings 38*(7), 814–823.

Brandon, G. and A. Lewis (1999). Reducing household energy consumption: a qualitative and quantitative field study. *Journal of Environmental Psychology 19*(1), 75–85.

BRE (2013). Mean household temperatures. Technical report.

Breukers, S. C., E. Heiskanen, B. Brohmann, R. M. Mourik, and C. F. J. Feenstra (2011, 4). Connecting research to practice to improve energy demand-side management (dsm). *Energy 36*(4), 2176–2185. ID: 17.

British gas (2016). Hive active heating.

BSRIA (2007). How many politicians does it take to change a lightbulb?

Buswell, R. (2013). Uncertainty in whole house monitoring. *In proceedings of 2013 Conference in Building Simulation.*

Buswell, R. A., D. Marini, L. Webb, and M. Thomson (2013). Determining heat use in residential buildings using high resolution gas and domestic hot water monitoring.

Caird, S., R. Roy, and H. Herring (2008). Improving the energy performance of UK households: Results from surveys of consumer adoption and use of low-and zero-carbon technologies. *Energy Efficiency 1*(2), 149–166.

CALORIELAB, INC. (2015). Calorie counter.

Cameron, S. (2011). *Handbook on the Economics of Leisure.* Edward Elgar Publishing.

Carbon Trust (2011). Energy and carbon convertions 2011 update. Technical report.

Centre for Sustainable Energy (2008). How low: achieving optimal carbon savings from the UKs existing housing stock. Technical report, Association for the conservation of Energy andMoore, R.

Cheng, V. and K. Steemers (2011). Modelling domestic energy consumption at district scale: A tool to support national and local energy policies. *Environmental Modelling & Software 26*(10), 1186–1198.

Coleman, M., N. Brown, A. Wright, and S. K. Firth (2012). Information, communication and entertainment appliance useinsights from a UK household study. *Energy and Buildings.*

Commission of Sustainable Development (2006). Stock take, delivering improvements in existing housing. *SDC, London.*

Committee on Climate Change (2015). 5th carbon budget. Technical report.

Control4 (2014). Home automation and solutions for everyone.

Cosar-Jorda, P. and R. A. Buswell (2015). Estimating the air change rates in dwellings using a heat balance approach. *Energy Procedia 78*, 573–578.

Cosar-Jorda, P., R. A. Buswell, and V. Mitchell (2013). Estimating the potential reductions in energy demand through efficiency, control and lifestyle change in a real home.

Cosar-Jorda, P., R. A. Buswell, L. Webb, K. Leder Mackley, R. Morosanu, and S. Pink (2013). Energy in the home: Everyday life and the effect on time of use.

Coughlan, T., M. Brown, S. Martindale, R. Comber, T. Ploetz, K. L. Mackley, V. Mitchell, and S. Baurley (2013). Methods for studying technology in the home. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*, pp. 3207–3210. ACM.

Critchley, R. and D. Phipps (2007). Water and energy efficient showers: Project report. *United Utilities and Liverpool John Moores University, Liverpool.*

Crosbie, T. and K. Baker (2010). Energy-efficiency interventions in housing: learning from the inhabitants. *Building Research & Information 38*(1), 70–79.

Crump, D., S. Dimitroulopoulou, R. Squire, D. Ross, B. Pierce, M. White, V. Brown, and S. Coward (2005). Ventilation and indoor air quality in new homes. *Pollution atmosphérique 1*, 71.

Darby, S. (2006). The effectiveness of feedback on energy consumption. *A Review for DEFRA of the Literature on Metering, Billing and direct Displays 486*, 2006.

Darby, S. (2010). Smart metering: what potential for householder engagement? *Building Research & Information 38*(5), 442–457.

Darby, S. and E. McKenna (2012, 10). Social implications of residential demand response in cool temperate climates. *Energy Policy 49*(0), 759–769. ID: 21.

Department for Business, Energy and Industrial Strategy (2016). *Digest of United Kingdom energy statistics 2016.* The Stationery Office.

Department for Communities and Local Government (2010). Approved document f: Means of ventilation, nbs. Technical report.

Department for Communities and Local Government (2012). English housing survey. headline report 2011-2012. Technical report.

Department for Communities and Local Government (2015). Dwelling stock estimates 2014, england. Technical report.

Department for Communities and Local Government (2016). English housing survey headline report 2014-15. Technical report.

Department for Environment Food and Rural Affaires (2007). The social cost of carbon and the shadow price of carbon: What they are, and how to use them in economic appraisal in the UK. economics group,. Technical report.

Department of Energy & Climate Change (2009). Smarter grids: the opportunity. Technical report.

Department of Energy & Climate Change (2010). 2050 pathways. Technical report.

Department of Energy & Climate Change (2011a). The carbon plan: Delivering our low carbon future. Technical report.

Department of Energy & Climate Change (2011b). *Planning our electric future: a white paper for secure, affordable and low-carbon electricity*, Volume 8099. Stationery Office.

Department of Energy & Climate Change (2012a, 31 January 2013). Energy consumption in the united kingdom: 2012. Technical report.

Department of Energy & Climate Change (2012b). The energy efficiency strategy: The energy efficiency opportunity in the UK. Technical report.

Department of Energy & Climate Change (2012c). The future of heating and climate change: A strategic framework for low carbon heat in the UK. Technical report.

Department of Energy & Climate Change (2013). UK housing energy fact file. Technical report.

Department of Energy & Climate Change (2015a). Average annual domestic gas bills for gb regions with average unit costs. Technical report.

Department of Energy & Climate Change (2015b). Energy consumption in the united kingdom (ecuk); chapter 3. Technical report.

Department of Environment Transport and the Regions (2000). English house condition survey 1996: Energy report. Technical report.

Department of Trade and Industry (2007). Energy white paper 2007 meeting the energy challenge.

DG Environment (June 2010). Green public procurement, windows technical background report . Technical report.

Dick, J. (1950). The fundamentals of natural ventilation of houses. *Journal of the Institution of Heating and Ventilating Engineers 18*(179), 123–134.

Dimitroulopoulou, C. (2012). Ventilation in european dwellings: A review. *Building and Environment 47*, 109–125.

Directive, E. (2012). 27/eu of the european parliament and of the council of 25 october 2012 on energy efficiency, amending directives 2009/125/ec and 2010/30/eu and repealing directives 2004/8/ec and 2006/32. *European Commission*.

DoE (2012). Building energy software tools directory.

DoE and W. OFFICE (1994). *Building Regulations 1991 Approved Document, Part L: Conservation of Fuel and Power.* 1995 Edition, London, HMSO.

E-on (28 de Septiembre de 2016). `https://www.eonenergy.com/for-your-home`.

EIA (2016). International energy outlook 2016. Technical report.

Electrical Energy Meters (2002). Ec requirements the measuring instruments (amendment).

Electricity Network Strategy Group (2010). A smart grid routemap. Technical report.

Emenius, G., A. Egmar, and M. Wickman (1998). Mechanical ventilation protects one-storey single-dwelling houses against increased air humidity, domestic mite allergens and indoor pollutants in a cold climatic region. *Clinical and Experimental Allergy 28*, 1389–1396.

Emenius, G., J. Korsgaard, and M. Wickman (2000). Window pane condensation and high indoor vapour contribution-markers of an unhealthy indoor climate? *Clinical and Experimental Allergy 30*(3), 418–425.

Energy Saving Trust (2002). Cavity wall insulation: Unlocking the potential in existing dwellings. Technical report.

Energy Saving Trust (2006). The rise of the machines: A review of energy using products in the home from the 1970s to today. Technical report.

Energy Saving Trust (2008a). Measurement of domestic hot water consumption in dwellings. *Energy Savings Trust*, 62.

Energy Saving Trust (2008b). Thermal transmittance of walls of dwellings before and after application of cavity wall insulation. Technical report.

Energy Saving Trust (2011a). The elephant in the living room: how our appliances and gadgets are trampling the green dream. Technical report.

Energy Saving Trust (2011b). Thermostats and controls.

Energy Saving Trust (2014a). Draught proofing.

Energy Saving Trust (2014b). Helping everyone save energy everyday.

European Commission (2016). Energy.

Ezratty, V., A. Duburcq, C. Emery, and J. Lambrozo (2009). Residential energy systems: links with socio-economic status and health in the lares study. *Housing and Health in Europe: The WHO LARES Project*, 155.

Fabi, V., R. V. Andersen, S. Corgnati, and B. W. Olesen (2012). Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment 58*, 188–198.

Fawcett, T. and T. Fawcett (2007). *Trialling Personal carbon allowances.* UKERC.

Firth, S., K. Lomas, A. Wright, and R. Wall (2008). Identifying trends in the use of domestic appliances from household electricity consumption measurements. *Energy and*

Buildings 40(5), 926–936.

Fisher, J. and K. Irvine (2010). Reducing household energy use and carbon emissions: the potential for promoting significant and durable changes through group participation. In *IESD PhD Conference: Energy and Sustainable Development*, pp. 49–57.

Frederick, S., G. Loewenstein, and T. O'donoghue (2002). Time discounting and time preference: A critical review. *Journal of economic literature 40*(2), 351–401.

Galvin, R. (2014). Estimating broad-brush rebound effects for household energy consumption in the eu 28 countries and norway: some policy implications of odyssee data. *Energy Policy 73*, 323–332.

Gardner, G. T. and P. C. Stern (1996). *Environmental problems and human behavior.* Allyn & Bacon.

Gatersleben, B. and C. Velk (1998). Household consumption, quality of life and environmental impacts: A psychological perspective and empirical study,. *Domestic consumers, environment, and sustainability.*

Geller, E. S. (2002). The challenge of increasing proenvironment behavior. *Handbook of environmental psychology 2*, 525–540.

Gram-Hanssen, K. (2010). Residential heat comfort practices: understanding users. *Building Research andInformation 38*(2), 175–186.

Greening, L. A., D. L. Greene, and C. Difiglio (2000). Energy efficiency and consumptionthe rebound effecta survey. *Energy policy 28*(6), 389–401.

Grid, N. (2015). National grid UK.

Grønhøj, A. and J. Thøgersen (2011). Feedback on household electricity consumption: learning and social influence processes. *International Journal of Consumer Studies 35*(2), 138–145.

Guerra-Santin, O. and L. Itard (2010). Occupants' behaviour: determinants and effects on residential heating consumption. *Building Research & Information 38*(3), 318–338.

Guo, J., J. Wu, and R. Wang (2011). A new approach to energy consumption prediction of domestic heat pump water heater based on grey system theory. *Energy and Buildings 43*(6), 1273–1279.

Hai-Xiang, Zhao, and F. Magoules (2012, 8). A review on the prediction of building energy consumption. *Renewable and Sustainable Energy Reviews 16*(6), 3586–3592.

Haines, V. and V. Mitchell (2014). A persona-based approach to domestic energy retrofit. *Building Research & Information 42*(4), 462–476.

Haldi, F. and D. Robinson (2011). The impact of occupants' behaviour on building energy demand. *Journal of Building Performance Simulation 4*(4), 323–338.

Hall, M. R., S. P. Casey, D. L. Loveday, and M. Gillott (2013). Analysis of UK domestic building retrofit scenarios based on the e.on retrofit research house using energetic hygrothermics simulation - energy efficiency, indoor air quality, occupant comfort, and mould growth potential. *Building and Environment 70*(0), 48–59.

Hargreaves, T., M. Nye, and J. Burgess (2010, 10). Making energy visible: A qualitative field study of how householders interact with feedback from smart energy monitors. *Energy Policy 38*(10), 6111–6119. ID: 25.

Hazas, M., A. Friday, and J. Scott (2011). Look back before leaping forward: Four decades of domestic energy inquiry. *IEEE pervasive Computing 10*, 13–19.

Heating and Hot Water Taskforce (2010). Heating and hot water pathways to 2020. Technical report.

Henderson, J. and J. Hart (2007). Bredem 2012; a technical description of the bre domestic energy model.

Hens, H., W. Parijs, and M. Deurinck (2010, 1). Energy consumption for heating and rebound effects. *Energy and Buildings 42*(1), 105–110.

Herkel, S., U. Knapp, and J. Pfafferott (2008, 4). Towards a model of user behaviour regarding the manual control of windows in office buildings. *Building and Environment 43*(4), 588–600.

HM Government (2010). The building regulations 2010: Conservation of fuel and power in existing dwellings.

Hoes, P., J. L. M. Hensen, M. G. L. C. Loomans, B. de Vries, and D. Bourgeois (2009, 3). User behavior in whole building simulation. *Energy and Buildings 41*(3), 295–302.

Home Heating Guide (2014). Sedbuk, boiler efficiency database.

Honeywell International Inc. (2014). evohome.

Hong, S. H., T. Oreszczyn, I. Ridley, and W. F. S. Group (2006). The impact of energy efficient refurbishment on the space heating fuel consumption in english dwellings. *Energy and Buildings 38*(10), 1171–1181.

Hong, T., S. D'Oca, W. J. Turner, and S. C. Taylor-Lange (2015). An ontology to represent energy-related occupant behavior in buildings. part i: Introduction to the dnas framework. *Building and Environment 92*, 764–777.

Hosni, M. H., B. W. Jones, and H. Xu (1999). Experimental results for heat gain and radiant/convective split from equipment in buildings. *ASHRAE Transactions 105*(1), 527–539.

Howard-Reed, C., L. A. Wallace, and W. R. Ott (2002). The effect of opening windows on air change rates in two homes. *Journal of the Air & Waste Management Association 52*(2), 147–159.

Hughes, N., J. Mers, and N. Strachan (2009). Review and analysis of UK and international low carbon energy scenarios. *UK Energy Research Centre*.

International Energy Agency (2013). Occupant behaviour and modeling. Technical report.

ISO, E. (2008). 13790: Energy performance of buildingscalculation of energy use for space heating and cooling (en iso 13790: 2008). *European Committee for Standardization (CEN), Brussels*.

Iwashita, G. and H. Akasaka (1997). The effects of human behavior on natural ventilation rate and indoor air environment in summera field study in southern japan. *Energy and Buildings 25*(3), 195–205.

Johnston, D., R. Lowe, and M. Bell (2005). An exploration of the technical feasibility of achieving co 2 emission reductions in excess of 60% within the UK housing stock by the year 2050. *Energy Policy 33*(13), 1643–1659.

Jones, P., S. Lannon, and J. Williams (2001). Modelling building energy use at urban scale. In *7th International IBSPA conference, Rio de Janeiro, Brazil, August*, pp. 1683–1697.

Kane, T., S. K. Firth, and K. J. Lomas (2015). How are UK homes heated? a city-wide, socio-technical survey and implications for energy modelling. *Energy and Buildings 86*, 817–832.

Karvonen, A. (2013). Towards systemic domestic retrofit: a social practices approach. *Building Research & Information 41*(5), 563–574.

Kashif, A., S. Ploix, J. Dugdale, and X. H. B. Le (2013). Simulating the dynamics of occupant behaviour for power management in residential buildings. *Energy and Buildings 56*, 85–93.

Kavgic, M., A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, and M. Djurovic-Petrovic (2010). A review of bottom-up building stock models for energy consumption in the residential sector. *Building and environment 45*(7), 1683–1697.

Keiding, L., L. Gunnarsen, N. Rosdahl, M. Machon, R. Møller, and O. K. L. Valbjørn (2003). Environmental factors of everyday life in denmark–with specific focus on housing environment. *Danish, with summary in English. Copenhagen: National Institute of Public Health*.

Khazzoom, J. D. (1989). Energy savings from more efficient appliances: a rejoinder. *The Energy Journal 10*(1), 157–166.

Kujala, S. (2003). User environment: a review of the benefits and challenges. *Behaviour &*

information technology, 1–16.

Kvisgaard, B. and P. Collet (1990). The users influence on air change. *Air change rate and airtightness in buildings*, 67–76.

Li, F. G., A. Smith, P. Biddulph, I. G. Hamilton, R. Lowe, A. Mavrogianni, E. Oikonomou, R. Raslan, S. Stamp, A. Stone, et al. (2015). Solid-wall u-values: heat flux measurements compared with standard assumptions. *Building Research & Information 43*(2), 238–252.

Lomas, K. J. (2010). Carbon reduction in existing buildings: a transdisciplinary approach.

Lopes, M. A., C. H. Antunes, A. Reis, and N. Martins (2016). Estimating energy savings from behaviours using building performance simulations. *Building Research & Information*, 1–17.

Loveday, D. L., T. Bhamra, T. Tang, V. J. A. Haines, M. J. Holmes, and R. J. Green (2008, 12). The energy and monetary implications of the 24/7 always on society. *Energy Policy 36*(12), 4639–4645.

Lutzenhiser, L. (1993). Social and behavioral aspects of energy use. *Annual Review of Energy and the Environment 18*(1), 247–289.

Mackey, C. and L. Wright (1944). Periodic heat flowhomogeneous walls or roofs. *ASHVE Transactions 50*(1994), 293–312.

Malkawi, A. and G. Augenbroe (2004). *Advanced building simulation.* Routledge.

Mallaband, B. (2013). *Integrating User Centred Design into the development of energy saving technologies.* Ph. D. thesis, Loughborough University Design School, © Becky Mallaband.

Mansouri, I., M. Newborough, and D. Probert (1996, 7). Energy consumption in UK households: Impact of domestic electrical appliances. *Applied Energy 54*(3), 211–285. ID: 46.

Market Transformation Programme (2006). Changing consumer lifestyles and their possible effects on future patterns of energy consumption.

Martinaitis, V., E. K. Zavadskas, V. Motuzien, and T. Vilutien (2015, 8/15). Importance of occupancy information when simulating energy demand of energy efficient house: A case study. *Energy and Buildings 101*, 64–75.

Mason, M. (2010). Sample size and saturation in phd studies using qualitative interviews. In *Forum Qualitative Sozialforschung/Forum: Qualitative Social Research*, Volume 11.

Mata, E., A. S. Kalagasidis, and F. Johnsson (2010). Assessment of retrofit measures for reduced energy use in residential building stockssimplified costs calculation. In *Proceedings of Sustainable Building Conference SB10mad. 28-30 April 2010, Madrid, Spain.*

MET office (2012, 3/8/2012). Met office surface data users guide.

Meyers, R. J., E. D. Williams, and H. S. Matthews (2010). Scoping the potential of monitoring and control technologies to reduce energy use in homes. *Energy and Buildings 42*(5), 563–569.

Molderink, A., V. Bakker, M. G. C. Bosman, J. L. Hurink, and G. J. M. Smit (2010). Management and control of domestic smart grid technology. *Smart Grid, IEEE Transactions on 1*(2), 109–119.

Moon, J. W. and S.-H. Han (2011). Thermostat strategies impact on energy consumption in residential buildings. *Energy and Buildings 43*(2), 338–346.

Mullaly, C. (1998, 12). Home energy use behaviour: a necessary component of successful local government home energy conservation (lghec) programs. *Energy Policy 26*(14), 1041–1052. ID: 42.

Natarajan, S., J. Padget, and L. Elliott (2011). Modelling UK domestic energy and carbon emissions: an agent-based approach. *Energy and Buildings 43*(10), 2602–2612.

National Grid (2011). UK future energy scenarios. Technical report.

Neto, A. H. and F. A. S. Fiorelli (2008). Comparison between detailed model simulation and artificial neural network for forecasting building energy consumption. *Energy and Buildings 40*(12), 2169–2176.

Nolan, J. M., P. W. Schultz, R. B. Cialdini, N. J. Goldstein, and V. Griskevicius (2008). Normative social influence is underdetected. *Personality and social psychology bulletin 34*(7), 913–923.

Offerman, F., J. Robertson, D. Springer, S. Brennan, and T. Woo (2007). Window usage, ventilation, and formaldehyde concentrations in new california homes: summer field sessions. *Healthy and Sustainable Buildings, ASHRAE*.

Office for National Statistics (2011). Home ownership and renting in england and wales detailed characteristics.

Office of the Deputy Prime Minister (2010, 25th of July 2014). The building regulations 2006 (f),a ventilation, approved document. Technical report.

Oreszczyn, T., S. H. Hong, I. Ridley, P. Wilkinson, and W. F. S. Group (2006). Determinants of winter indoor temperatures in low income households in england. *Energy and Buildings 38*(3), 245–252.

Orr, G., T. Lelyveld, and S. Burton (2009). Final report: In situ monitoring of efficiencies of condensing boilers and use of secondary heating. *Energy Saving Trust, London*.

OWL (2014). Intelligent wireless energy monitoring and control.

Palmborg, C. (1986, 7). Social habits and energy consumption in single-family homes. *Energy 11*(7), 643–650. ID: 43.

Parys, W., D. Saelens, and H. Hens (2011). Coupling of dynamic building simulation with stochastic modelling of occupant behaviour in offices–a review-based integrated methodology. *Journal of Building Performance Simulation 4*(4), 339–358.

Peeters, L., J. V. der Veken, H. Hens, L. Helsen, and W. Dhaeseleer (2008). Control of heating systems in residential buildings: Current practice. *Energy and Buildings 40*(8), 1446–1455.

Peng, C. and Z. Wu (2008). Thermoelectricity analogy method for computing the periodic heat transfer in external building envelopes. *Applied Energy 85*(8), 735–754.

Philips (2016). Hue personal wireless lighting.

Poortinga, W., L. Steg, C. Vlek, and G. Wiersma (2003, 2). Household preferences for energy-saving measures: A conjoint analysis. *Journal of Economic Psychology 24*(1), 49–64.

Porteous, C., T. Sharpe, R. Menon, D. Shearer, H. Musa, P. Baker, C. Sanders, P. Strachan, N. Kelly, and A. Markopoulos (2012). Energy and environmental appraisal of domestic laundering appliances. *Building Research & Information 40*(6), 679–699.

Price, P. N. and M. H. Sherman (2006). Ventilation behavior and household characteristics in new california houses. *Lawrence Berkeley National Laboratory*.

Protocol Kyoto (1997). United nations framework convention on climate change. *Kyoto Protocol, Kyoto 19*.

Quiggin, D. and R. Buswell (2016). The implications of heat electrification on national electrical supply-demand balance under published 2050 energy scenarios. *Energy 98*, 253–270.

Reeves, A., S. Taylor, and P. Fleming (2010). Modelling the potential to achieve deep carbon emission cuts in existing UK social housing: the case of peabody. *Energy Policy 38*(8), 4241–4251.

Richardson, I., M. Thomson, and D. Infield (2008). A high-resolution domestic building occupancy model for energy demand simulations. *Energy and Buildings 40*(8), 1560–1566.

Richardson, I., M. Thomson, D. Infield, and C. Clifford (2010). Domestic electricity use: A high-resolution energy demand model. *Energy and Buildings 42*(10), 1878–1887.

Roberts, S. and J. Thumim (2006). A rough guide to individual carbon trading. *The ideas, the issues and the next steps, Centre for Sustainable Energy, UK*.

Robson, C. (2011). *Real world research: a resource for users of social research methods in applied settings*. Wiley Chichester.

Rodriguez, E. and C. Boks (2005). How design of products affects user behaviour and vice versa: the environmental implications. In *Environmentally Conscious Design and Inverse*

Manufacturing, 2005. Eco Design 2005. Fourth International Symposium on, pp. 54–61. IEEE.

Roscoe, A. and G. Ault (2010). Supporting high penetrations of renewable generation via implementation of real-time electricity pricing and demand response. *IET Renewable Power Generation* (1752-1416). ID: 20.

Roulet, C.-A. (2002). pren-iso 13790–a simplified method to assess the annual heating energy use in buildings. *ASHRAE Transactions 108*, 911.

Rylatt, R., S. J. Gadsden, and K. J. Lomas (2003). Methods of predicting urban domestic energy demand with reduced datasets: a review and a new gis-based approach. *Building Services Engineering Research and Technology 24*(2), 93–102.

Saldanha, N. and I. Beausoleil-Morrison (2012, 6). Measured end-use electric load profiles for 12 canadian houses at high temporal resolution. *Energy and Buildings 49*(0), 519–530. ID: 49.

Samsung (2016). Smartthings.

Samuelson, C. D. (1990). Energy conservation: A social dilemma approach. *Social Behaviour 5*(4), 207–230.

Sangani, K. (2014). The heat is on.

Sanne, C. (2002). Willing consumers or locked-in? policies for a sustainable consumption. *Ecological Economics 42*(1), 273–287.

Santin, O. G. (2011). Behavioural patterns and user profiles related to energy consumption for heating. *Energy and Buildings 43*(10), 2662–2672.

Santin, O. G., L. Itard, and H. Visscher (2009). The effect of occupancy and building characteristics on energy use for space and water heating in dutch residential stock. *Energy and Buildings 41*(11), 1223–1232.

SAP BRE (2012). The governments standard assessment procedure for energy rating of dwellings. Technical report.

Schipper, L., A. Ketoff, and S. Meyers (1982). International residential energy demand use data: analysis of historical and present day structure and dynamics. *Energy 7*((2)), 205–206–212. ID: 41.

SEDBUK (2014, 29th of June 2014). Home heating guide, news, views and reviews on domestic central heating, boiler and renewable energy.

Seiders, D., G. Ahluwalia, S. Melman, R. Quint, A. Chaluvadi, M. Liang, A. Silverberg, C. Bechler, and J. Jackson (2007). Study of life expectancy of home components. *National Association Of Home Builders, Bank Of America Home Equity*.

Sheldon, L., T. Hartwell, B. Cox, J. Sickles, E. Pellizzari, M. Smith, R. Perritt, and S. Jones (1989). An investigation of infiltration and indoor air quality. *Final Report.NY State ERDA Contract No*.

Sherman, M. H. and W. R. Chan (2006). Building air tightness: research and practice. *Building Ventilation: the state of the Art*, 137–162.

Shipworth, M., S. K. Firth, M. I. Gentry, A. J. Wright, D. T. Shipworth, and K. J. Lomas (2010). Central heating thermostat settings and timing: building demographics. *Building Research and Information 38*(1), 50–69.

Shorrock, L. and J. Dunster (1997). The physically-based model brehomes and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock. *Energy Policy 25*(12), 1027–1037.

Shorrock, L., J. Henderson, and J. Utley (2005). *Reducing carbon emissions from the UK housing stock*. BRE Bookshop.

Shove, E. (2003). Converging conventions of comfort, cleanliness and convenience. *Journal of Consumer Policy 26*(4), 395–418.

Shove, E. and A. Warde (2002). Inconspicuous consumption: the sociology of consumption, lifestyles, and the environment. *Sociological theory and the environment: classical foundations, contemporary insights 230.*

Simpson, A. and G. Castles (1992). Measurements of heat losses from an insulated domestic hot water cylinder. *Building Services Engineering Research and Technology 13*(1), 43–47.

Simpson, S., P. Banfill, V. Haines, B. Mallaband, and V. Mitchell (2016). Energy-led domestic retrofit: impact of the intervention sequence. *Building Research & Information 44*(1), 97–115.

Skea, J., P. Ekins, and M. Winskel (2011). *Energy 2050: Making the transition to a secure low energy system.* Earthscan.

Sovacool, B. K., S. Ryan, P. Stern, K. Janda, G. Rochlin, D. Spreng, M. J. Pasqualetti, H. Wilhite, and L. Lutzenhiser (2015). Integrating social science in energy research. *Energy Research & Social Science 6*, 95–99.

Staley, B. C., S. Ladislaw, K. Zyla, and J. Goodward (2009). Evaluating the energy security implications of a carbon-constrained us economy.

Stankovic, L., V. Stankovic, J. Liao, C. Wilsaon, R. Hauxwell-Baldwin, and M. Coleman (2015). Understanding domestic appliance use through their linkages to common activities. In *Proc. EEDAL-2015 8th Int. Conf. Energy Effi ciency in Domestic Appliances and Lighting, Lucerne-Horw, Switzerland.*

Stanton, N. A., M. S. Young, and C. Harvey (2014). *Guide to Methodology in Ergonomics: Designing for Human Use.* CRC Press.

Summerfield, A., R. Lowe, H. Bruhns, J. Caeiro, J. Steadman, and T. Oreszczyn (2007). Milton keynes energy park revisited: Changes in internal temperatures and energy usage. *Energy and Buildings 39*(7), 783–791.

Sundell, J., M. Wickman, G. Pershagen, and S. Nordvall (1995). Ventilation in homes infested by housedust mites. *Allergy 50*(2), 106–112.

Swan, L. G. and V. I. Ugursal (2009, 10). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews 13*(8), 1819–1835.

Tang, T. and T. Bhamra (2009). Improving energy efficiency of product use: an exploration of environmental impacts of household cold appliance usage patterns.

The Chartered Institution of Building Services Engineers, London (2005). Guide b : Heating, ventilating, air conditioning and refrigeration. Technical report.

The Chartered Institution of Building Services Engineers, London (2006). Guide a : Environmental design. Technical report.

The Engineering tool box (2016). The engineering tool box.

The Midlands Energy Consortium (2013). Calebre: Consumer appealing low energy technologies for building retrofitting.

The Technology Strategy Board (2009). Evaluating the energy security implications of a carbon constrained u.s. economy. Technical report.

The Technology Strategy Board (2013, 17 of April 2013). Retrofit revealed. the retrofit for the future projects-data analysis report. Technical report.

The Technology Strategy Board (2014). Reducing energy use in existing homes a guide to making retrofit work. Technical report.

Time Inc.UK Ltd Technology Network (2016).

Toftum, J. (2010, 1). Central automatic control or distributed occupant control for better indoor environment quality in the future. *Building and Environment 45*(1), 23–28.

Tompros, S., N. Mouratidis, M. Draaijer, A. Foglar, and H. Hrasnica (2009). Enabling applicability of energy saving applications on the appliances of the home environment. *IEEE network 23*(6), 8–16.

Transition Network (2013). Transition Network.Org.

UK Energy Research Centre (2009). Making the transition to a secure and low carbon energy system:synthesis report.

UK Parliament (2008). Climate change act 2008. *London: The Stationery Office Limited*.

University of Wisconsin–Madison. Solar Energy Laboratory and Klein, Sanford A (1979). Trnsys, a transient system simulation program.

Ürge-Vorsatz, D., A. Novikova, S. Köppel, and B. Boza-Kiss (2009). Bottom–up assessment of potentials and costs of CO_2 emission mitigation in the buildings sector: insights into the missing elements. *Energy Efficiency 2*(4), 293–316.

U.S Department of Energy (2007). What are greenhouse gases? Technical report.

U.S Department of Energy (2015). Energy plus energy simulation software.

Utley, J. and L. Shorrock (2008). Domestic energy fact file 2008. Technical report.

Vadodaria, K., D. L. Loveday, V. Haines, V. Mitchell, B. Mallaband, and S. H. Bayer (2010). UK solid-wall dwellings-thermal comfort, energy efficiency refurbishment and the user perspective-some preliminary analysis from the calebre project.

Vera Control Ltd (2014). Smarter home control.

Wall, R. and T. Crosbie (2009). Potential for reducing electricity demand for lighting in households: An exploratory socio-technical study. *Energy Policy 37*(3), 1021–1031.

Wallace, L., S. Emmerich, C. Howard-Reed, and L. C. Dr (2002). Continuous measurements of air change rates in an occupied house for 1 year: the effect of temperature, wind, fans, and windows. *Journal of exposure analysis and environmental epidemiology 12*(4), 296–306.

Wallace, L., W. Nelson, T. Hartwell, J. Keever, L. Michael, R. Perritt, J. Sebestik, D. Smith, and E. Pellizzari (1988). Preliminary results from the baltimore team study.

Wang, X., Z. Chen, C. Yang, and Y. Chen (1999). Gray predicting theory and application of energy consumption of building heat-moisture system. *Building and Environment 34*(4), 417–420.

Warde, A. (2005). Consumption and theories of practice. *Journal of consumer culture 5*(2), 131–153.

Weiss, M., C.-M. Loock, T. Staake, F. Mattern, and E. Fleisch (2010). Evaluating mobile phones as energy consumption feedback devices. In *International Conference on Mobile and Ubiquitous Systems: Computing, Networking, and Services*, pp. 63–77. Springer.

Weiss, M., M. K. Patel, M. Junginger, and K. Blok (2010). Analyzing price and efficiency dynamics of large appliances with the experience curve approach. *Energy Policy 38*(2), 770–783.

Wilhite, H., H. Nakagami, T. Masuda, Y. Yamaga, and H. Haneda (1996). A cross-cultural analysis of household energy use behaviour in japan and norway. *Energy Policy 24*(9), 795–803.

Williams, A. (2014). Bre: The future of electricity in domestic buildings. Technical report.

Wilson, C. and H. Dowlatabadi (2007). Models of decision making and residential energy use. *Annual review of environment and resources 32*(1), 169.

Wilson, C., T. Hargreaves, and R. Hauxwell-Baldwin (2013). Using smart homes: Themes, linkages, and disconnects in research on smart homes and their users. *Joint Science, Society and Sustainability 3*.

Wilson, I. G., A. J. Rennie, Y. Ding, P. C. Eames, P. J. Hall, and N. J. Kelly (2013). Historical daily gas and electrical energy flows through great britain's transmission networks and the decarbonisation of domestic heat. *Energy Policy 61*, 301–305.

Wolfe, P. (2008, 12). The implications of an increasingly decentralised energy system. *Energy Policy 36*(12), 4509–4513.

Wood, G. and M. Newborough (2003). Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. *Energy and buildings 35*(8), 821–841.

Wookey, R., A. Bone, C. Carmichael, and A. Crossley (2014). Minimum home temperature thresholds for health in winter–a systematic literature review. Technical report.

Wright, A. (2008). What is the relationship between built form and energy use in dwellings? *Energy Policy 36*(12), 4544–4547.

Yohanis, Y. G. (2012, 2). Domestic energy use and householders' energy behaviour. *Energy Policy 41*(0), 654–665. ID: 39.

Yu, Z., B. C. M. Fung, F. Haghighat, H. Yoshino, and E. Morofsky (2011, 6). A systematic procedure to study the influence of occupant behavior on building energy consumption. *Energy and Buildings 43*(6), 1409–1417.

Yu, Z. J., F. Haghighat, B. C. M. Fung, E. Morofsky, and H. Yoshino (2011, 11). A methodology for identifying and improving occupant behavior in residential buildings. *Energy 36*(11), 6596–6608.

Zadeh, S. M., D. V. Hunt, and C. D. Rogers (2014). Socio-technological influences on future water demands. *Water 6*(7), 1961–1984.

Zhou, Q., S. Wang, X. Xu, and F. Xiao (2008). A grey-box model of next-day building thermal load prediction for energy-efficient control. *International Journal of Energy Research 32*(15), 1418–1431.

Zimmermann, J.-P., M. Evans, J. Griggs, N. King, L. Harding, P. Roberts, and C. Evans (2012). Household electricity survey: A study of domestic electrical product usage. *Intertek Testing & Certification Ltd.*

Appendix A

Uncertainty analysis

In this appendix the uncertainty of the approach is rationalised and estimated, describing the error sources for each parameter and quantifying its impact on the uncertainty of the output parameter Q_v.

Natural ventilation in domestic buildings is a complex parameter to model since there are a high number of variables that impact on the air changes per hour. These are: the difference of temperature between the inside and the outside, the infiltration paths within the dwelling, the wind characteristics at the house position, the position and size of windows and doors frames, the opening of these and the orientation of the house, the opening length of opened windows and doors and the use of fans and other systems affecting the air flow in the house. For the estimation of the ventilation variable in this analysis some of these variables have been monitored and others have been simplified applying standard values from collected data about the house and published figures used for the estimation of infiltration and ventilation variables. The limitations of the approach are therefore, those linked with the simplification of the parameters used within the calculation, that from applying mathematical equations to represent a real process and those resulting from the use of monitoring data. The uncertainty of the approach is studied by estimating each models parameter uncertainty to then calculate the uncertainty of the output variable Q_v.

A.1 Gas

There are a number of assumptions and empirical uncertainties linked to the estimation of gas. Firstly, the calorific value $C_{v_{gas}}$ is considered constant at 39.5 MJm^{-3}, when in reality there is a variation on the calorific value of gas, which fluctuates with gas composition. The published $C_{v_{gas}}$ fluctuation at the national Grid for 2013 in the UK is from 35 MJ/m^{-3} to 41 MJ/m^{-3} (Grid, 2015). These figures are calculated under standard conditions (temperature 15℃ and pressure 1013.25 millibars) at a number of UK stations, and therefore there are two main sources of error when using the published annual average $C_{v_{gas}}$. The error linked to the assumption that gas heating power at the supply location does not vary (conditions as in the standard) and the error from applying an average figure when in reality it is constantly varying. The uncertainty analysis considers an error linked to the parameter $C_{v_{gas}}$ of ± 1.5 MJ based in previous work by (Buswell, 2013).

The boiler efficiency ϵ has been assumed based on published efficiencies for each boiler model at SEDBUCK (Home Heating Guide, 2014). The uncertainty linked to the boiler efficiency is complex to evaluate as the efficiency of the boiler varies considerably with its maintenance, settings, time of the year, and the use of the boiler to supply space heating and hot water or only hot water. A proxy uncertainty figure of 4% has been used for all boilers ϵ based on previous work by (Orr et al., 2009), which studied the boiler efficiency standard deviation of a set of combination boilers and tanks compared to those figures published by SEDBUCK, reporting a deviation of 4% for combination boilers and 3% for regular boilers.

The volume of gas data has an uncertainty figure linked to the monitoring equipment and the conversion process from graphical to numerical data. The calibration uncertainty of the meter is considered ± 3%, a figure taken from the statutory requirement for European meter accuracy. The conversion process error is taken from previous empirical work, which was calculated based on a sample of gas by estimating the 95% confidence limits over 1 minute, resulting in an error of 7% (Buswell, 2013).

$$Q_g = C_{v_{gas}} \cdot V_g \cdot \epsilon \tag{A.1}$$

Table A.1: Gas uncertainty variables.

Parameter	**Uncertainty value**	**Unit**	**Reference**
Calorific value	±1.5	MJ	(Buswell, 2013), (Grid, 2015)
Volume of gas	±3	%	Statutory requirements
Data processing	±7	%	(Buswell, 2013)
Boiler efficiency	±4	%	(Orr et al., 2009)
Energy conversion	-	-	Constant

$$U_{Q_g} = \sqrt{(\frac{\delta Q_g}{\delta C_{v_{gas}}} U_{Cv_{gas}})^2 + (\frac{\delta Q_g}{\delta V_g} U_{Vg})^2 + (\frac{\delta Q_g}{\delta \epsilon} U_{boiler})^2} \tag{A.2}$$

$$U_{Q_g} = \sqrt{(V_g \cdot \epsilon \cdot U_{Cv})^2 + (Cv_{gas} \cdot \epsilon \cdot U_{Vg})^2 + (V_g \cdot Cv_{gas} \cdot tU_{boiler})^2} \tag{A.3}$$

A.2 Hot water

The uncertainty of the hot water flow is that from the meter, which is considered from the statutory requirements for European meter accuracy (±3%). Water temperature sensors have an uncertainty of ±0.5K as indicated by the sensors supplier; however sensors measure water temperature on the outside of the copper pipe, which is also affected by the ambient conditions. The typical boiler output flow temperatures has been observed to be in the region of 40 ℃ to 60 ℃, depending on boiler type and settings. Ambient conditions are between 18 ℃ and 25 ℃, that due to the monitoring technique, will impact on the temperature recording. However, for the estimation of hot water energy consumption, only the temperature difference before and after going into the boiler is used, therefore the errors are correlated, as both sensors are placed under equal conditions. The error is therefore considered negligible.

The specific water heat capacity's uncertainty is considered to be zero as for the water density, neglecting any deviation caused by water composition and temperature (The Engineering tool box, 2016).

$$m_w = flow_w \cdot \rho \tag{A.4}$$

$$Q_{w_{use}} = \Delta T m_w \cdot Cp_w \tag{A.5}$$

Table A.2: Hot water uncertainty variables.

Parameter	**Uncertainty value**	**Unit**	**Reference**
Temperature difference (ΔT_{water})	0	-	Correlated
Water flow	±3	%	Statutory requirements
Water mass	0	-	Negligible
Specific heat	0	-	Negligible
Water density	0	-	Negligible

$$U_{Q_{w_{use}}} = \sqrt{(\frac{\delta Q_{w_{use}}}{\delta flow} U_{flow})^2} \tag{A.6}$$

$$U_{Q_{w_{use}}} = \sqrt{(\Delta T_{water} \cdot Cp_w \cdot U_{flow})^2} \tag{A.7}$$

A.2.1 Hot water energy output

To estimate the energy output from hot water, the difference of temperature from the water going out of the boiler and that when leaving the house is considered. For the uncertainty of temperature out of the boiler, sensors precision of 0.5 K is applied; for hot water temperature when leaving the house, an uncertainty of ± 3 ℃ is considered, as this value is assumed as constant at 18 ℃, when in reality temperature will be heavily dependent on initial and ambient temperature. Flow sensors precision is estimated at ±3 % from the European meter accuracy. The error from water specific heat capacity is considered negligible as for water density.

Table A.3: Hot water uncertainty variables.

Parameter	**Uncertainty value**	**Unit**	**Reference**
T out the boiler	±0.5	℃	(Buswell, 2013)
T final	±3	℃	judgement
Water flow	±3	%	Statutory requirements
Water density	0	-	Negligible
Specific heat	0	-	Negligible

$$Q_{w_{loss}} = (Tw_{out} - Tw_f) \cdot V_w \cdot Cp_w \tag{A.8}$$

$$U_{Qw_{loss}} = \sqrt{(\frac{\delta Qw_{loss}}{\delta \Delta T})^2 + (\frac{\delta Qw_{loss}}{\delta V_w})^2} \tag{A.9}$$

$$U_{Qw_{loss}} = \sqrt{(V_w \cdot Cp_w \cdot U_{\Delta T})^2 + (\Delta T \cdot Cp_w \cdot U_{Vw})^2} \tag{A.10}$$

A.3 Space heating

The uncertainty in the estimation of space heating consumption is accounted within the calculation of gas and hot water uncertainties, calculated as the residual between overall measured gas consumption and calculated hot water consumption.

$$Q_{sh} = Q_g - Q_{w_{use}} \tag{A.11}$$

A.4 Electricity

The uncertainty in the electricity measurements is related to the assumed and actual variability of the supply voltage and the precision of the current measurement, as apparent power is inferred from CTs, which monitors current flow (I) in a conductor and converts it into apparent power ($P_a = V \cdot I$) by assuming a voltage (V). The Electricity supply regulations (SI 1994, No.3021) states that tab voltage tolerance of 230V is within 6%, +10%. Current is converted to power assuming the voltage, considering an error of ±10% on the current (Buswell, 2013) Also, the device calibration and manufacturing variability which affects current assignment, impacts on the uncertainty, in particular the low current characteristic behaviour. To evaluate this, a small number of CTs were subjected to varying loads (17W, 40W, 60W, 1.3kW, 2.6kW) to ascertain the reading error. The real power was measured by a Multicube digital power meter with an accuracy of $U_{cal} \pm 1\%$.

The heat input into the space from electricity is considered to be 100%, as the estimation is performed on a daily basis, assuming that all heat from electric power has been reabsorbed into the space, regardless of the heat source. The only exception is for electric showers, where energy output is considered to leave the space with the resultant hot water going through the drain at a specific temperature. An approximation is used in this case to assume that a quarter of the consumption results in a gain into the space, as suggested by The Governments Standard Assessment Procedure for Energy Rating of Dwellings (SAP BRE, 2012).

Table A.4: Power uncertainty variables.

Parameter	**Uncertainty value**	**Unit**	**Reference**
Apparent power	10	%	SI 1994, No.3021
Conversion factor (WMJ)	-	-	-

$$Q_e = H_r \cdot P \cdot WMJ \tag{A.12}$$

$$U_{Q_e} = \sqrt{U_{CT}}^2 \tag{A.13}$$

A.5 People heat input

The heat input from occupants is estimated based on a number of assumptions which uncertainties are analysed here. The metabolic rate from family members has been simplified to a constant value that represents the heat production of a person seated at rest. The value is adapted for female, male and child members, regardless of the activity they do in the home, their weight and further factors that in reality affects heat production. The metabolic rate uncertainty has been considered to be 10% of the given figure as heat production can heavily vary depending on the activity performed in the house, being as low as 100 W when resting or as high as 350 W if running around and playing with children or animals. Nevertheless the duration of these activities is usually short compared with resting time, and most studies assume occupants resting heat production (The Chartered Institution of Building Services Engineers, London, 2006). The uncertainty linked to occupants' heat production is considered plus or minus 10% (CALORIELAB, INC., 2015) of the heat rate.

The number of people at home is assumed from household profiles that describes typical occupancy over weekdays and weekend days based on reported data from householders. Nevertheless, the uncertainty of the occupied time and number of people is considered to be high, as family schedules continuously change. The uncertainty is assumed to be 30% for the occupancy time and number of occupants within the house. The uncertainty in the occupancy time is assessed from the assumption that during the week the daily schedule is maintained, whereas the weekends can vary from week to week. Therefore the low range of occupancy would consider non occupancy during the weekend whereas the high occupancy range would considered whole occupancy during the weekend. This is translated into a 30% possible error. For the number of people at home, the range of error is considered as for the occupancy time: 30%.

Table A.5: Uncertainty variables from the occupancy profiles.

Parameter	**Uncertainty value**	**Unit**	**Reference**
Metabolic rate	10	%	judgement
Number of people at home	30	%	judgement
time in the house	30	%	judgement

$$Q_p = M_r \cdot N_p \cdot t_i \cdot WMJ \tag{A.14}$$

$$U_{Q_p} = \sqrt{(\frac{\delta Qp}{\delta M_r} U_{M_r})^2 + (\frac{\delta Qp}{\delta N_p} U_{N_p})^2 + (\frac{\delta Qp}{\delta t_i} U_{t_i})^2} \tag{A.15}$$

$$U_{Q_p} = \sqrt{(M_r \cdot WMJ \cdot t_i \cdot U_{N_p})^2 + (M_r \cdot WMJN_p \cdot U_{t_i})^2 + (N_p \cdot t_i \cdot WMJ \cdot U_{M_r})^2} \tag{A.16}$$

A.6 Solar gains

Solar gains are calculated by applying the BREDEM method. The input parameters for the calculation are: the vertical solar flux, which is monitored by MIDAS and used in the analysis. Its uncertainty is assumed to be 10% as the MIDAS database does not give a figure for monitoring precision but a number of error sources such as poor exposure, dirt, moisture or frost.

The frame factor is assumed from that published in BREDEM, differentiating between window frames materials (wood, metal and PVC). The frame material data is collected from on-line participants questionnaires. The uncertainty linked to the frame factor is 0.1 (dimensionless), considering the potential error from the wrong participants answer about their frame materials (difference between metal and wood/PVC) for cases where the frame material is not clear. This error would cover any proportion of windows frame that are different to the main type and that have not been asked in the survey. The glazing transmission variable has a potential error of 0.3 (dimensionless), as this is the maximum difference of glazing transmission factor on a given glazing but different materials.

The solar access is the variable with higher uncertainty as it has been assumed unknown conditions, applying BREDEM figures for those cases where the shading conditions are not known. Considering that shading can block from 20 to 80 % of solar gains a potential error of 60% is applied.

Finally, an uncertainty of 1% is assigned to windows area, evaluating a possible error during the collection of data of 1 cm for each meter measured.

Table A.6: Solar estimation uncertainty variables.

Parameter	Uncertainty value	Unit	Reference
Vertical solar flux (Fx)	10	%	judgement
Frame Factor (FF)	0.1	-	judgement
Solar Access (SA)	60	%	judgement
Glazing transmission factor (G_f)	0.03	-	judgement
Windows area (A_w)	1	%	judgement

$$Q_s = FF \cdot SA \cdot 0.9 \cdot Fx \cdot G_f \cdot A_w \tag{A.17}$$

$$U_{Q_s} = \sqrt{(\frac{\delta Q_s}{\delta FF}U_{FF})^2 + (\frac{\delta Q_s}{\delta SA}U_{SA})^2 + (\frac{\delta Q_s}{\delta Fx}U_{F}x)^2 + (\frac{\delta Q_s}{\delta G_f}U_{G_f})^2 + (\frac{\delta Q_s}{\delta A_w}U_{A_w})^2} \tag{A.18}$$

A.7 Fabric heat loss

Fabric conditions and temperature difference are important sources of error in the heat balance calculation, as heat through the fabric is one one of the most important heat processes within the house, especially when the heating is on and ΔT is high. Assumptions on those variables can originate important differences between modelled and real energy dynamics in buildings, which in this case will influence the dependent variable Q_v.

Possible errors from poor quality dimension measurements are considered to be 1% of the area. Differences between selected U values and real transmission factors are considered to be 10%, as there are a number of uncertainty sources impacting on this, such as: differences between building fabric techniques and materials, quantity and concrete characteristics, humidity within the fabric, and other contextual factors that have not been assessed. Also, there is uncertainty from possible differences between real building elements and assumed building elements that are originated from poor profiles, as these are built based on participants knowledge of their dwelling. Therefore a potential error of 5% is also applied to the U value.

Temperature sensors position: temperature outside is measured in situ in every dwelling by using DOR sensors, magnetic monitors that record the temperature of the surface attached; the location of the sensor affects the temperature measurement and it is expected to show variations for different surfaces and for different faades even in a single dwelling. The outside temperature used for the calculation is the daily mean outside temperature of the dwellings.

Table A.7: Fabric heat loss uncertainty variables.

Parameter	Uncertainty value	Unit	Reference
Building el. area (A_f)	1	%	judgement
U value (U_f)	10	%	(Baker, 2011)
Building characteristics information	5	%	judgement
Temperature out		℃	(MET office, 2012)
Temperature in	0.9	℃	(Buswell, 2013)

The indoors temperature is measured in a number of rooms per house. In order to simplify the calculation, the average temperature between the sensors inside is calculated and used for the estimation. Since ventilation is a physical process that heavily depends on the difference of temperature between the inside and outside this output error is one of the main sources of uncertainty. For bulk average indoor temperature, 0.9 ℃ error is considered from previous work which studies uncertainty of room bulk average temperature using the same sensors (Buswell, 2013).

$$Q_f = \sum_{i=1}^{x} A_{fi} U_{fi} \Delta T_i \tag{A.19}$$

$$U_{Qf} = \sqrt{(\frac{\delta Qf}{\delta \Delta T} U_{\Delta T})^2 + (\frac{\delta Qf}{\delta U_f} U_{Uf})^2 + (\frac{\delta Qf}{\delta A} U_A)^2} \tag{A.20}$$

A.8 Ventilation

The uncertainty in the ventilation heat exchange is estimated as the result from applying all the uncertainties in the independent parameters that conforms the output Q_V. This is estimated as shown in Equation A.21.

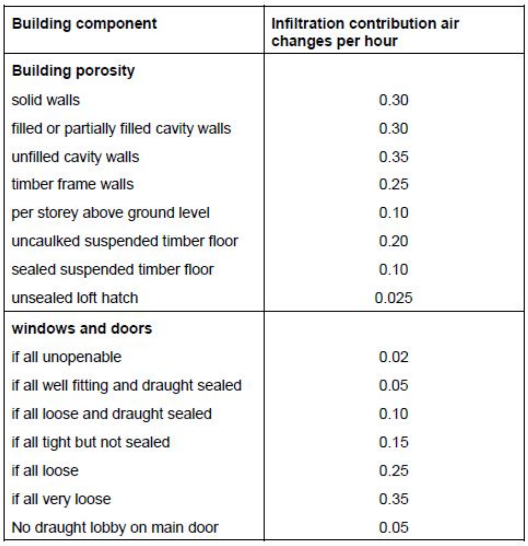
$$U_{Qv} = \sqrt{U_{Q_{sh}}^2 + U_{Q_{wuse}}^2 + U_{Qe}^2 + U_{Qp} + U_{Qs}^2 + U_{Q_{wloss}}^2 + U_{Qf}^2} \tag{A.21}$$

The ventilation rate N was calculated using Equation 4.19 and its uncertainty was evaluated applying the following equation:

$$U_N = \sqrt{(\frac{\delta N}{\delta Qv} U_{Qv})^2 + (\frac{\delta N}{\delta \Delta T} U_{\Delta T})^2 + (\frac{\delta N}{\delta V_{house}} U_{Vhouse})^2} \tag{A.22}$$

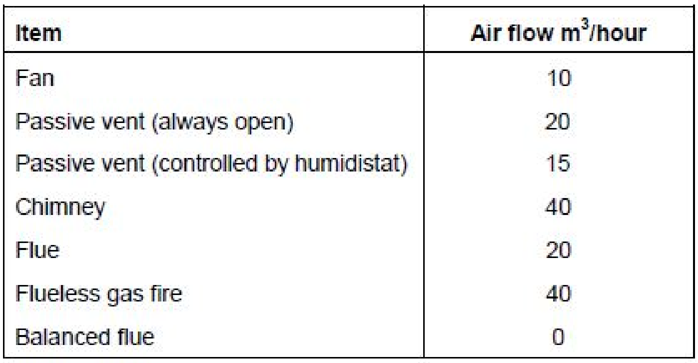
Appendix B

Values from BREDEM tables



Building component	Infiltration contribution air changes per hour
Building porosity	
solid walls	0.30
filled or partially filled cavity walls	0.30
unfilled cavity walls	0.35
timber frame walls	0.25
per storey above ground level	0.10
uncaulked suspended timber floor	0.20
sealed suspended timber floor	0.10
unsealed loft hatch	0.025
windows and doors	
if all unopenable	0.02
if all well fitting and draught sealed	0.05
if all loose and draught sealed	0.10
if all tight but not sealed	0.15
if all loose	0.25
if all very loose	0.35
No draught lobby on main door	0.05

Figure B.1: Building fabric contribution values.

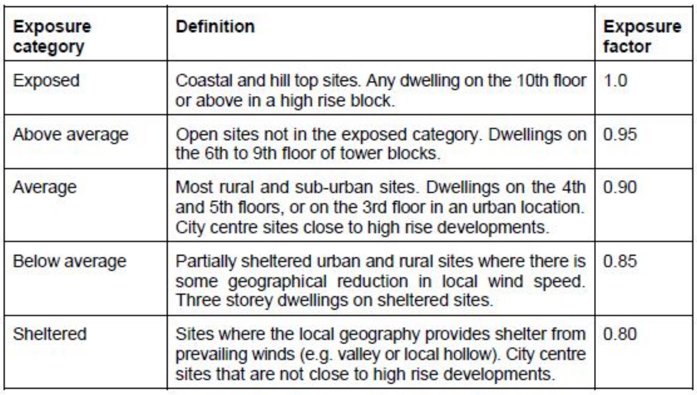


Item	Air flow m^3/hour
Fan	10
Passive vent (always open)	20
Passive vent (controlled by humidistat)	15
Chimney	40
Flue	20
Flueless gas fire	40
Balanced flue	0

Figure B.2: Air flow rate for fans, flues and chimneys values.

Definition	Dwelling exposure
Exposed all four sides	1.0
Exposed three sides	0.95
Exposed two sides	0.90
Exposed one side	0.85
Fully sheltered	0.80

Figure B.3: Site exposure factors values.



Exposure category	Definition	Exposure factor
Exposed	Coastal and hill top sites. Any dwelling on the 10th floor or above in a high rise block.	1.0
Above average	Open sites not in the exposed category. Dwellings on the 6th to 9th floor of tower blocks.	0.95
Average	Most rural and sub-urban sites. Dwellings on the 4th and 5th floors, or on the 3rd floor in an urban location. City centre sites close to high rise developments.	0.90
Below average	Partially sheltered urban and rural sites where there is some geographical reduction in local wind speed. Three storey dwellings on sheltered sites.	0.85
Sheltered	Sites where the local geography provides shelter from prevailing winds (e.g. valley or local hollow). City centre sites that are not close to high rise developments.	0.80

Figure B.4: Dwelling exposure factors values.

Appendix C

Interview documents

Table of results

	I would do it						
Would you be willing to apply the following measures in your house?	**Already done it**	**Today (0 - 6 months)**	**Near future (1-5 years)**	**Long term future (more than 5 years time)**	**I only would do it if….**	**I would not do it at all because...**	**Comments**
Minimum* opening (windows/doors)							
New boiler							
17C maximum indoor air temp.							
Manual zone heating							
Triple glazing							

Interview notes:

First call information:

Aim of the study:

The purpose of this study is to investigate the reality of applying energy savings interventions in family homes. The interview aims at understanding about the reasons that can drive householders to change their behavior or invest in technology that saves energy and look at possible barriers that stop them applying those interventions.

Would you like to take part?

What is involved in taking part?

- 2 hours interview
- Ideally both adults attending (or the whole family)
- Information sheet and consent form

When would it be possible?

Introduce the scene:

1. My interest: The aim of the study and the main research question.
2. What I need from you: Your views and opinions based on what I am going to present to you.
3. Interview plan:
    I. Your data and the comparison with 2050 targets
    II. Possible interventions to save energy and the reality of applying them in everyday life.

Over the interview:

1. Explain the approach, limitations and assumptions. (mix of real data and estimations, values apply)
2. Bring ICT and innovation points for discussion.

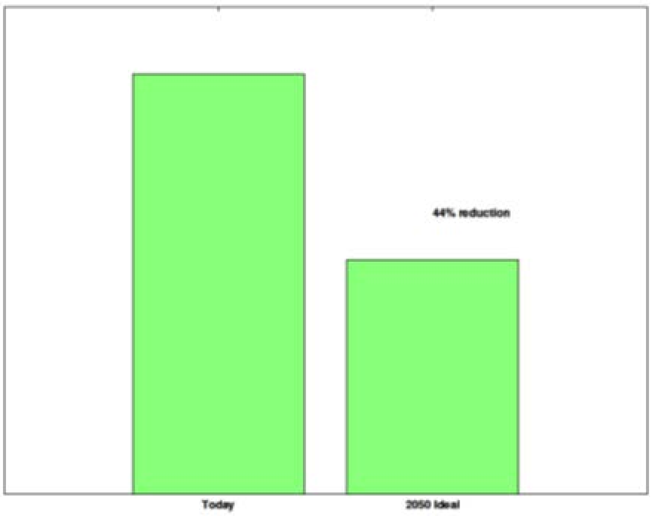
Other questions/concerns:

1. Can they keep the graphs?

Interview questions

1. How realistic do you think it is to get to 2050 target energy demand savings?

2. Are those targets relevant for you?



3. Is energy reduction relevant for you for any other reason?

Cards: Possibilities for savings

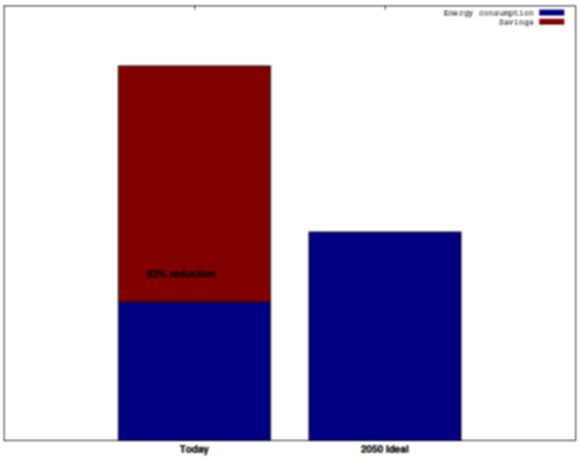
4. What do you think you can do in order to save energy in your house?

5. Can you rank your savings ideas from the one which saves more energy to the least one?

Our findings.

III. Explain the approach and limitations

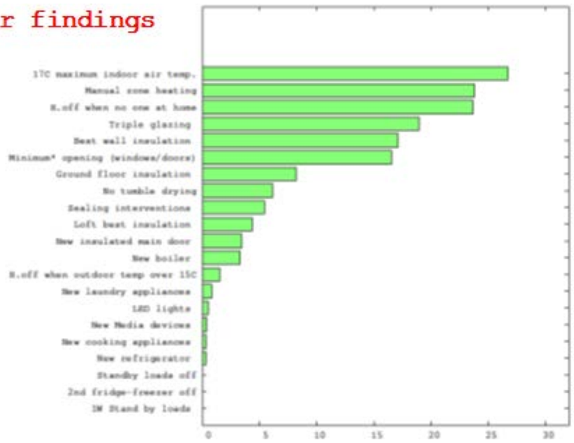
6. Do you think this is feasible?



Explain one by one the interventions applied.

7. Is it very different to their first thoughts? Compare with their ranking.

Our findings



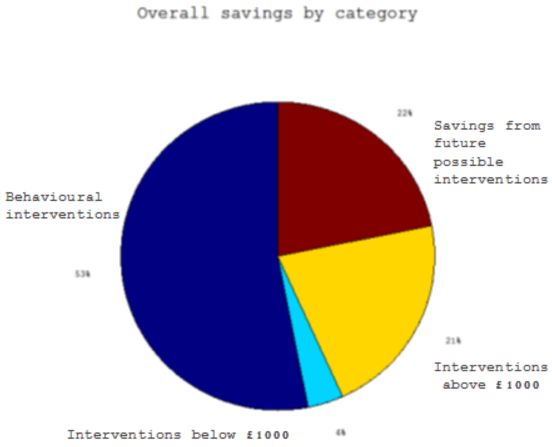
*New: Best efficient device (either in the market or expected to enter the market in the near future)
*Sealing interventions: Blocking chimneys, sealing skirting boards, service pipes, boiler flue, removing kitchen fans or insulate under-croft.
*Closing windows and doors to a minimum: Theoretical approach by applying minimum fresh air standards

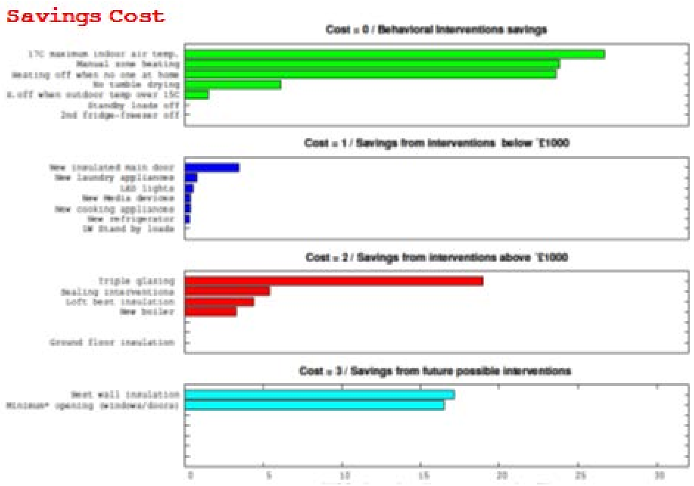
8. What do you think of each of the savings? Did any of them surprise you?

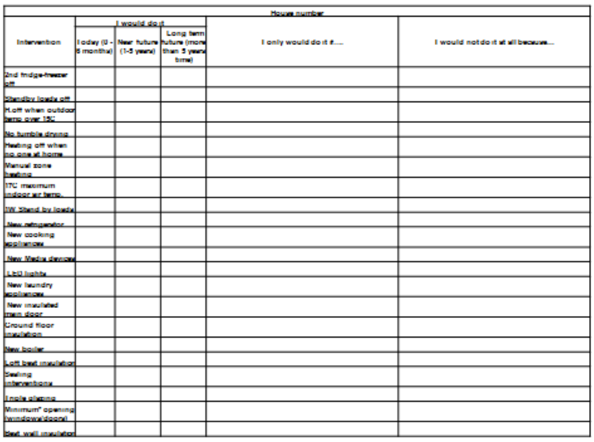
9. Is there any interventions we didn't model? If so why? Can we model it?

Introduce the 4 categories

10. How would you have categorise the savings?







House number					
Intervention	I would do it			I only would do it if....	I would not do it at all because...
	Today (0 - 6 months)	Near future (1-5 years)	Long term future (more than 5 years time)		
2nd fridge-freezer off					
Standby loads off					
H.off when outdoor temp over 15C					
No tumble drying					
Heating off when no one at home					
Manual zone heating					
17C maximum indoor air temp.					
1W Stand by loads					
New refrigerator					
New cooking appliances					
New Media devices					
LED lights					
New laundry appliances					
New insulated main door					
Ground floor insulation					
New boiler					
Loft best insulation					
Sealing interventions					
Triple glazing					
Minimum* opening (windows/doors)					
Best wall insulation					

Present the different interventions and discuss which of the savings they would apply and why, which not, what are the barriers… together with the answer sheet table.

Your view:

11. Did you change your view about potential savings in the home?

12. Now that we have gone throw potential savings from a number of interventions, how realistic do you think 2050 energy demand targets are?

13. Did you find the analysis interesting?

14. Do you trust the results?

15. Do you think the information was clear?

16. What did you miss in the discussion?

17. What would you need (or what can help you) in order to apply savings? What technology/ mobile application/ device (anything really) would help you to achieve savings?

Appendix D

Self reported on-line survey

Submission Date:

Section 1: A

1. What is your property type?
House
Bungalow
Flat
Apartment
Maisonette
1.a. Do you have a conservatory?
Yes
No
Will have one in the next 12 months
1.a.i. If you anwered yes to a conservatory, is the conservatory heated?
Yes
No

2. What style of home do you live in?
Detached
Semi-detached
Mid-terrace
End-terrace
Mid-terrace back to back
End-terrace back to back

3. In which year was your home built?
Before 1900
1900 - 1929
1930 - 1949
1950 - 1965
1966 - 1974
1975 - 1981
1982 - 1990
1991 - 1995
1996 - 2002
2002 - 2006
After 2007

4. Has your property been extended?
Yes
No
Not sure

5. How many storeys does your property have?
1
2
3
4

6. How many rooms do you have in your home?
6.a. Do you have a garage?
No
Single
Double
Triple
Fully integrated
Partly integrated
Totally detached

7. What is your main wall type?
Timber frame
Insulated cavity
Uninsulated cavity
Solid brick
Stone

Section 2: B

8. Where is your gas meter located?
In an external box
In an internal box or cupboard
Under the stairs
In the garage
8.a. How often do you read your gas meter?
Once per week
Once per month

Once per quarter
Once per year
Never

9. Where is your electric meter located?
In an external box
In an internal box or cupboard
Under the stairs
In the garage
9.a. How often do you read your electric meter?
Once per week
Once per month
Once per quarter
Once per year
Never
9.b. Do you currently use electrical power and/or energy monitoring devices in your home, such as OWL, AlertMe, etc?
No
At main incoming supply to house
For appliances via wall sockets
For appliances via fuse box

10. What type of energy supply tariff do you have?
Single fuel
Dual fuel
Dual fuel plus other utility
Not sure
10.a. How much, approximately, do you pay for your gas each year?
Up to £200
£200 - £400
£400 - £600
£600 - £800
£800 - £1,000
£1,000+
10.b. How much, approximately, do you pay for electricity each year?
Up to £200
£200 - £400
£400 - £600
£600 - £800
£800 - £1,000

£1,000+

11. What type of internet do you have at home?
None
Dial up
Broadband via wired router
Broadband via wireless (WiFi) router

Section 3: C

12. Is your house double glazed?
No
Partly
Fully

13. Are all your exterior doors and windows draught-proofed?
Yes
No
Partly
Not sure

14. What is the average thickness of insulation in your loft space?
None
Up to 50 mm
50 - 100 mm
100 - 150 mm
150 - 200 mm
200 - 250 mm
Over 250 mm
Not sure

Section 4: D

15. What is the main fuel used to heat your home?
Gas
Electricity
Oil
Coal

Wood

16. What is your main heating system?
Boiler supplying radiators
Boiler supplying underfloor heating
Warm air
Storage heaters
Open fires

17. If main system uses a boiler, how old is the boiler?
0 to 4 years
5 to 8 years
9 to 12 years
more than 12 years
17.a. How often is your boiler and/or central heating system serviced?
Twice a year
Once per year
Once every 2 years
Less than every 2 years
Not sure

18. If your main heating system uses a boiler, what type of boiler is it?
Non-condensing with hot water cyclinder in airing cupboard
Condensing with hot water cylinder in airing cupboard
Non-condensing combination ("combi")
Condensing combination
Back boiler

19. What heating controls does your heating system have?
Room thermostat (fixed to wall)
Room thermostat (moveable)
Programmer with simple time-clock
Programmer with multiple temperature/time settings
19.a. Do you have thermostatic control valves (TRVs) fitted to your radiators?
On all
On some
On none
19.b. During the heating season (i.e. winter months), which method(s) do you use to control your central heating system?
System on constantly

Raising / lowering room thermostat setting
Manual on / off switch for central heating boiler
1 timed heating period per day
2 or more timed heating periods per day
Central heating water temperature control
Adjustment of radiator valves
Variable thermostat settings and time periods depending on day of week
19.c. What temperature do you set on your central heating thermostat?
Less than 16 C
16 - 18 C
19 - 20 C
21 - 22 C
23 - 24 C
More than 24 C
Depends on how cold we feel
Depends on outside temperature

20. How is your hot water for personal washing and baths normally heated in the cooler months?
Main heating system
Electric immersion heater
Instant (in-line) electric water heater
Range

21. How is your hot water for personal washing and baths normally heated in the warmer months?
Main heating system
Electric immersion heater
Instant (in-line) electric water heater
Range

22. How do you heat water for personal showers in your home?
Same as main hot water system
Immersion heater
Electric (in-line) shower
22.a. How many showers of each type do you use?
None
1 Hot Water System
2 Hot Water System
3 Hot Water System
1 Electric in-line

2 Electric in-line
3 Electric in-line

Section 5: E

23. Which fuel do you use for hob cooking?
Gas
Electric
Both

24. Which fuel do you use for grill and oven cooking?
Gas
Electricity
Both

25. How often, roughly, do you boil your electric kettle each day?
0
1 - 2
3 - 4
5 - 6
7 - 8
8+

26. Which of the following laundry appliances do you use routinely?
Automatic washing machine
Spin dryer
Tumble dryer
Steam iron
26.a. In a typical week, how many times do you use your washing machine?
1-3
4-6
7-9
10 or more
26.b. If you use a tumble dryer, in a typical week how many times do your operate it?
1-3
4-6
7-9
10 or more

27. Which of the following cooling appliances do you use?
Fridge
Freezer (upright and chest)
Fridge-freezer
American style (side by side) fridge-freezer
Wine conditioner

28. Which is your primary method of washing up dishes?
Manually
Dishwasher
Both equally
28.a. If you use a dishwasher, in a typical week how many times do you operate it?
1-3
4-6
7-9
10 or more

29. What proportion of your internal lights is fitted with low energy compact fluorescent light (CFL) bulbs?
All
More than half
Roughly half
Less than half
None

Section 6: F

30. Do you have a dimensioned drawing of your home?
Yes
No
I'd be willing to generate a drawing myself
I'd be willing to allow the LEEDR team to generate a drawing
30.a. Are you willing to allow the LEEDR team to photograph the location and model details of your main appliances?
Yes
No
With some reservations

Section 7: G

31. How long have you lived in your current home?
0 - 2 years
3 - 5 years
5 - 10 years
More than 10 years

32. What is the age range of adult 1?
20 - 25
26 - 35
36 - 45
46 - 55
56 - 65
65+
32.a. What is the training / education level of adult 1?
GCSE / GCE
A Level
NVQ
HND
HNC
Diploma
Degree
Higher degree
Lifetime of experience

33. What is the age range of adult 2?
Not applicable
20 - 25
26 - 35
36 - 45
46 - 55
56 - 65
65+
33.a. What is the training / education level of adult 2?
GCSE / GCE
A Level
NVQ
HND

HNC
Degree
Higher degree
University of Life

34. What is the age range of adult 3?
Not applicable
20 - 25
26 - 35
36 - 45
46 - 55
56 - 65
65+

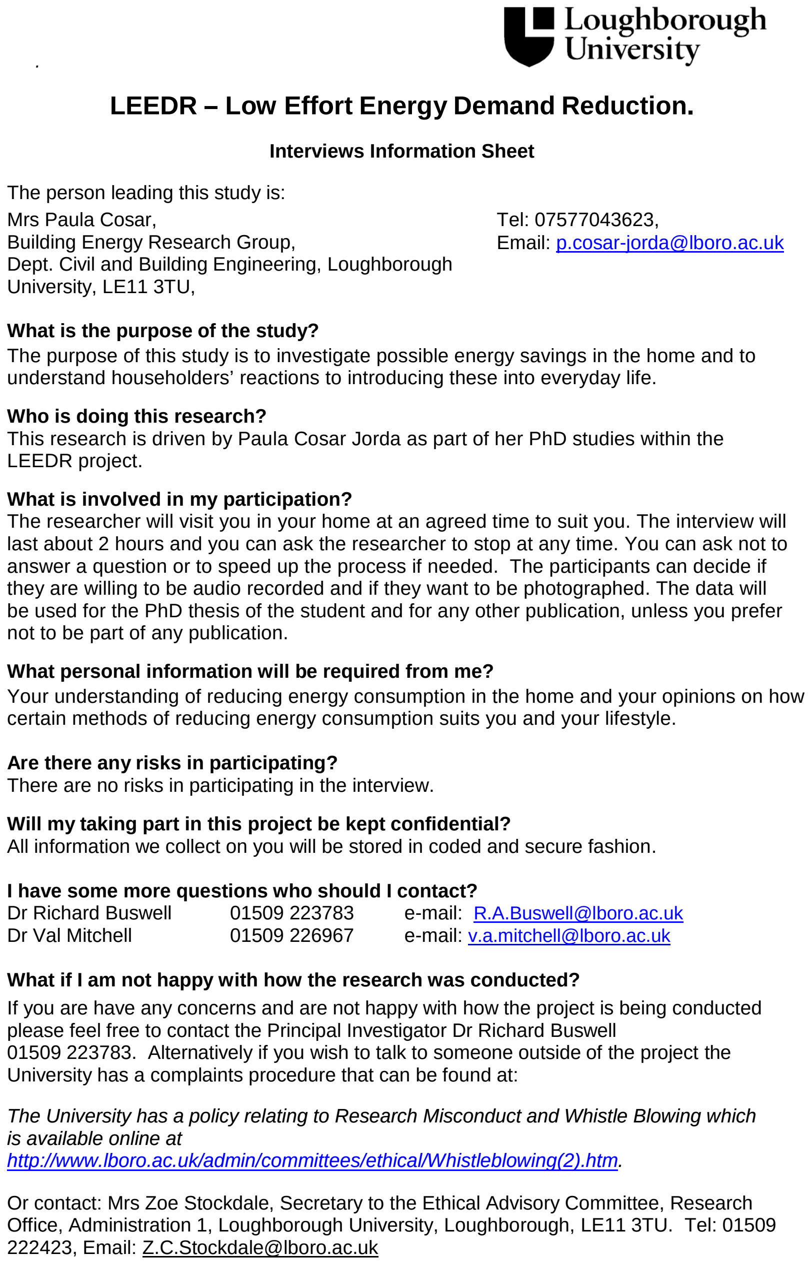
35. What is your approximate household annual net income? NB While this information would be helpful to the LEEDR team, we wish to emphasise this question is absolutely optional.
Up to £20,000
£20,000 to £30,000
£30,000 to £40,000
£40,000 to £50,000
Over £50,000

36. How many children and young people aged 0 to 19 live with you permanently?
0
1
2
3
4
5+
36.a. What are their ages?

37. In a typical week, very roughly what proportion of time is your home occupied during Monday to Friday period?
90 - 100%
80 - 90%
70 - 80%
60 - 70%
50 - 60%
Less than 50%

Appendix E

Ethics



Loughborough University

LEEDR – Low Effort Energy Demand Reduction.

Interviews Information Sheet

The person leading this study is:

Mrs Paula Cosar,
Building Energy Research Group,
Dept. Civil and Building Engineering, Loughborough University, LE11 3TU,

Tel: 07577043623,
Email: p.cosar-jorda@lboro.ac.uk

What is the purpose of the study?

The purpose of this study is to investigate possible energy savings in the home and to understand householders' reactions to introducing these into everyday life.

Who is doing this research?

This research is driven by Paula Cosar Jorda as part of her PhD studies within the LEEDR project.

What is involved in my participation?

The researcher will visit you in your home at an agreed time to suit you. The interview will last about 2 hours and you can ask the researcher to stop at any time. You can ask not to answer a question or to speed up the process if needed. The participants can decide if they are willing to be audio recorded and if they want to be photographed. The data will be used for the PhD thesis of the student and for any other publication, unless you prefer not to be part of any publication.

What personal information will be required from me?

Your understanding of reducing energy consumption in the home and your opinions on how certain methods of reducing energy consumption suits you and your lifestyle.

Are there any risks in participating?

There are no risks in participating in the interview.

Will my taking part in this project be kept confidential?

All information we collect on you will be stored in coded and secure fashion.

I have some more questions who should I contact?

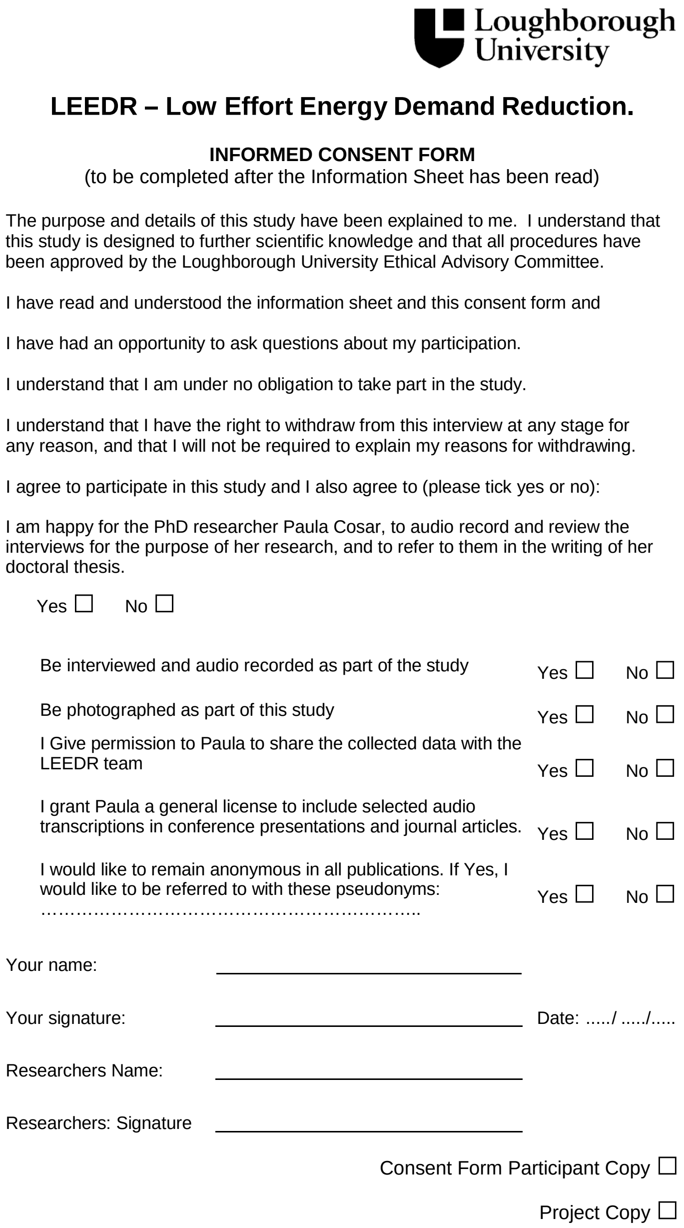
Dr Richard Buswell	01509 223783	e-mail: R.A.Buswell@lboro.ac.uk
Dr Val Mitchell	01509 226967	e-mail: v.a.mitchell@lboro.ac.uk

What if I am not happy with how the research was conducted?

If you are have any concerns and are not happy with how the project is being conducted please feel free to contact the Principal Investigator Dr Richard Buswell 01509 223783. Alternatively if you wish to talk to someone outside of the project the University has a complaints procedure that can be found at:

The University has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Or contact: Mrs Zoe Stockdale, Secretary to the Ethical Advisory Committee, Research Office, Administration 1, Loughborough University, Loughborough, LE11 3TU. Tel: 01509 222423, Email: Z.C.Stockdale@lboro.ac.uk



Loughborough University

LEEDR – Low Effort Energy Demand Reduction.

INFORMED CONSENT FORM
(to be completed after the Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form and

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this interview at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I agree to participate in this study and I also agree to (please tick yes or no):

I am happy for the PhD researcher Paula Cosar, to audio record and review the interviews for the purpose of her research, and to refer to them in the writing of her doctoral thesis.

Yes ☐ No ☐

Be interviewed and audio recorded as part of the study	Yes ☐	No ☐
Be photographed as part of this study	Yes ☐	No ☐
I Give permission to Paula to share the collected data with the LEEDR team	Yes ☐	No ☐
I grant Paula a general license to include selected audio transcriptions in conference presentations and journal articles.	Yes ☐	No ☐
I would like to remain anonymous in all publications. If Yes, I would like to be referred to with these pseudonyms: ………………………………………………………..	Yes ☐	No ☐

Your name: ______________________________

Your signature: ______________________________ Date: ...../ ...../.....

Researchers Name: ______________________________

Researchers: Signature ______________________________

Consent Form Participant Copy ☐

Project Copy ☐

Figure E.1: Interviews consent form