The role of user centred design in domestic energy demand reduction

by

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ABSTRACT

The domestic sector currently accounts for approximately a third of the UK's energy use and so energy demand reduction in the domestic sector is a key part of the UK's strategy for carbon reduction. However, energy demand reduction has typically been addressed from an engineering perspective, with little consideration of the requirements of users. This PhD submission aims to identify how qualitative information about users' experiences, values and practices relating to UK domestic energy demand reduction can be collected and presented effectively to an engineering audience and incorporated into engineering-focused energy research. User centred design is presented as a viable approach to understanding the context of energy use in UK homes and specifying requirements of the householders; as a way of ensuring user needs are included in this socio-technical problem space. This requires presentation of information about human behaviour in a form that is timely and appropriate to the engineering audience, who take a positivist view, preferring facts and figures to descriptions and anecdotes.

A collection of nine publications, mostly peer-reviewed journal papers, by the thesis author and her co-authors is presented. Publications spanning from 2006 to 2014 illustrate a range of approaches to providing user centred information, from literature review to complex householder studies, which can provide information to enhance the engineering data and so provide additional insight and understanding. The research findings within the individual papers add to the body of knowledge on domestic energy use. In addition, the research identifies a number of roles where user centred design contributes to understanding of home energy use. From providing background and raising awareness of the presence of users within a system, to contextual understanding and the specification of user requirements, through to more sophisticated user characterisation, it is argued that user centred design can offer a significant contribution to the field. Future application of user information into engineering models, together with large scale, longitudinal studies of home energy use are proposed, building on the contributions of this thesis.

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- The other eleven co-authors on the included publications, whose contributions to those papers enabled me to progress to this stage.
- The participants who took part in the various studies reported. Although unnamed, they are essential to the research and their involvement is much appreciated.
- The funders of the underlying research, who are acknowledged in the individual publications.
- My family, who has tolerated me spending hours at the weekend at the dining room table on the latest draft of various papers. Tom, Matilda and Alex, I can't promise it will stop, but I do really appreciate the love and support.

Thank you all.

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The problem, of course, is the humans
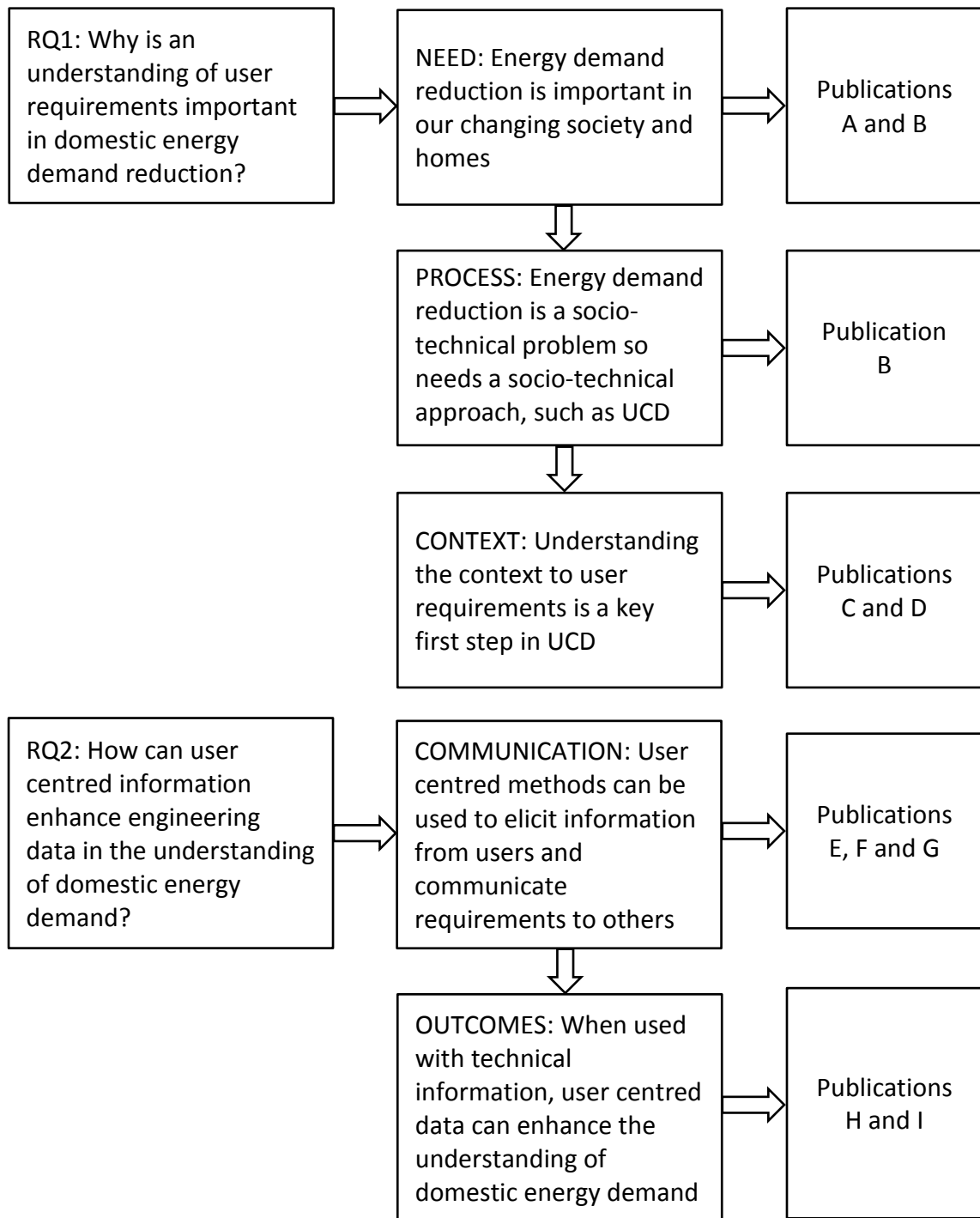
CHAPTER 1: INTRODUCTION

1   Introduction

This thesis presents a selection of publications with the aim of identifying how qualitative information about users' experiences, values and practices relating to UK domestic energy demand reduction can be collected and presented effectively to an engineering audience and incorporated into engineering-focused energy research. Engineers tend to focus on objectivity and explore the world through positivism; that is, that reality "exists external to the researcher and must be investigated through the rigorous process of scientific inquiry" (Gray, 2014:21). But the methods underpinning user centred design, the approach taken by the author, are often grounded in subjective data, with the meaning constructed by the researcher. This creates a tension between the contributions of the user centred design specialist and the engineer that requires careful handling. The publications in this thesis demonstrate a range of approaches to ease this tension, with examples of how user centred data can be presented to the engineer so that it is of value.

Two central research questions drive the enquiry:

1. Why is an understanding of user requirements important to domestic energy demand reduction research?
2. How can user centred information enhance engineering data in the understanding of domestic energy demand?

A total of nine publications are presented, each of which contribute in some way towards the overall aim. Research question 1 is addressed by publications A, B, C and D (going from the general to a specific case study). Research Question 2 is addressed by publications E, F, G, H and I which show examples of the communication of user centred data in practice and how this can be combined with more traditional engineering data, to enhance understanding of energy use. This is illustrated in Figure 1 overleaf.

RQ1: Why is an understanding of user requirements important in domestic energy demand reduction?	NEED: Energy demand reduction is important in our changing society and homes	Publications A and B
	PROCESS: Energy demand reduction is a socio-technical problem so needs a socio-technical approach, such as UCD	Publication B
	CONTEXT: Understanding the context to user requirements is a key first step in UCD	Publications C and D
RQ2: How can user centred information enhance engineering data in the understanding of domestic energy demand?	COMMUNICATION: User centred methods can be used to elicit information from users and communicate requirements to others	Publications E, F and G
	OUTCOMES: When used with technical information, user centred data can enhance the understanding of domestic energy demand	Publications H and I

Figure 1. The contribution of the publications towards the thesis research questions

1.1 Context to the thesis

With binding government targets to reduce the amount of carbon emissions being produced (Great Britain, Climate Change Act, 2008) and limited stocks of fossil fuels, reducing energy demand has become a key focus for the UK. Over the past 40 years, since the oil crisis of the 1970s, technical and engineering solutions have been developed to improve the supply of energy and increase efficiency. However, in the past decade, policy makers, manufacturers and the research community have increasingly realised that human intervention can significantly impact on the advances made by the technology alone and the energy saving incurred. Janda's (2011) paper "Buildings don't use energy, people do" sums up the realisation that the user must be considered in the system if maximum efficiency is to be achieved. Wilhite *et al*., (2000) identify that there has been an increasing knowledge of behaviour in this area, but this does not necessarily translate to an understanding of people's impact on energy demand. In short, we are beginning to understand *what* people do in the home, but not *why* and importantly, what can be *done* to reduce the energy impact.

In the past, technical interventions, by measuring and modelling a building's physical performance, reducing heat loss, increasing efficiency of supply and improving energy management, dominated the research community's approach to energy demand reduction, with a focus on non-domestic buildings (see, for example, Firth *et al.*, 2010). An awareness of the importance of understanding the occupants in domestic energy use started with Post-Occupancy Evaluation (POE) which has provided the primary and most consistently applied mechanism for collecting occupants' feedback about buildings over the past 40 years. Bordass and Leaman (2005) identify the origins of POE to the 1963 Royal Institute of British Architects' Plan of Work for Design Team Operation, which included 'Stage M – Feedback'. From these early days, Zimring and Reizenstein (1980) describe POE as the examination of the effectiveness for human users of occupied designed environments; trying to describe rather than manipulate user opinions of a building. More recently, Nicol and Roaf (2005) refer to POE as being concerned with the individual buildings in which the survey is being conducted; the focus is on the building, or the building management system, not the occupants.

Over a similar time period, human thermal comfort has been explored in detail, initially defined by Fanger in his seminal book "Thermal Comfort" (1970) and more recently expanded to include adaptive thermal comfort (Brager and de Dear, 1998; Nicol and Humphreys, 2002). Both these models provide an understanding of the physiological response to the thermal environment and have led to the standardisation of comfort conditions and control technology advances to provide energy efficient heating and cooling of buildings, again, primarily non-domestic. Occupant behaviour has also been studied though large scale surveys of homes (e.g. Andersen *et al.*, 2009) and through occupancy patterns (e.g. Yohanis *et al.*, 2008) but all these evaluation approaches do not fully explore the underlying experiences and expectations of the occupant, nor their values and goals and so are only likely to provide a superficial understanding of the users.

The housing sector contributes 29% of all energy used in the UK (Palmer and Cooper, 2013), of which 80% is for space heating and hot water provision. Clearly, the need to reduce energy demand in housing is significant but the issues involved in doing so are complex and interrelated. Whilst policy measures attempts to encourage and support individuals towards reducing their domestic energy demand and scientific advance progresses the technical measures available, there is a complexity to the problem that requires an holistic or systems perspective. Rittel and Webber (1973) described these types of societal problems as 'wicked' problems; they are ill-defined, they have no clear 'stopping point', they may only achieve a 'good enough' end point, they are without a time span, and the solutions are intertwined with the problem. As domestic energy demand reduction is a wicked problem with complex socio-technical components, the discipline of human factors lends itself well to offering an approach, or suite of approaches towards its better understanding. By focusing on the needs of the user and considering the range of activities undertaken in the context of the wider environment, it is possible to see beyond individual technical solutions to individual problems and consider the issue from a broader perspective. User centred design offers a process by which the user is considered central to the system and design solutions (which could be products, services or systems); it provides a means to ensure the context of use and user needs are understood and included within the design process, by considering the range of physical, cognitive, social, and cultural factors, with the focus on the needs of the user as a central tenet.

And so an approach where both social and technical factors are considered (Lomas, 2010), and with a central focus on the user, seems ideal to advance the understanding of energy demand reduction.

This work is not in isolation. The general field has been referred to as ergoecology (Garcia-Acosta et al, 2012, 2014), a multidisciplinary field to tackle the socio-technical systems in relation to ecosystems. Lange-Morales et al (2014) apply human factors and ergonomics perspectives to the wider issue of sustainability and Thatcher (2013) conceptualises 'green ergonomics' to describe ergonomics interventions with a pro-nature emphasis. Hanson (2013) also uses the term green ergonomics and highlights the potential of ergonomics/ human factors in the design of systems and products that reduce energy usage and waste. In 2013, a special issue of the journal Ergonomics focused on sustainability. In it, Haslam and Waterson (2013) highlight the limited ergonomics investigation or research explicitly contextualised as addressing sustainability per se. Zink and Fischer (2013) explore the relationship between ergonomics and sustainability, asking if sustainability is a necessary part of the discipline. Hedge et al (2010) highlight the inclusion of ergonomics within the US LEED (Leadership in Energy and Environmental Design) rating system, but this is applied primarily to non-domestic buildings. None of these specifically focus on the role of user centred design in energy demand reduction.

This thesis presents research by the author that explores this proposition further, within the UK domestic sector, then demonstrates through examples, different ways to collect and present user centred information. Finally, examples of combining user and technical data show how each enriches the other towards a better understanding of the problem in hand.

2 The role of user centred design in domestic energy demand reduction

The first research question asks: Why is an understanding of user requirements important in domestic energy demand reduction? The first three publications in this thesis, A, B and C, provide the context to this question. Publication A, a review based on literature and expert knowledge from the authors, demonstrates how the changing nature of society is affecting energy demand, and how the roles of design, energy management and new technology can be used to control the increasing demand. Society's increasing expectation of being able to use services and technology throughout the day and night means that the potential to use energy '24/7' is increased. Design, technology and energy management systems can help limit the wasted energy consumption, and in some cases, help spread the peak load of energy demand; the paper illustrates some examples of how this can be done. Publication B develops the context further through a review of literature, by focusing on energy demand reduction in homes, and introduces how user centred design can help, through exploring context of use and specifying user requirements before design solutions are developed and evaluated. This paper draws upon the user centred design process described in the International Standard, ISO 9241-210:2010 Ergonomics of human-system interaction (ISO, 2010) which provides an overview of human-centred design activities. Whilst the Standard focuses on interactive systems, this process can be taken in its broadest sense to cover any system with which a human interacts. In the Standard, the term "human" is used rather than "user" to emphasise that all stakeholders in the process should be considered, not just the typical end user; however, in this thesis, the two terms are considered as interchangeable. The process of human-centred design set out in ISO 9241 is shown in Publication B and includes the following key stages:

- Understand and specify the context of use
- Specify the user requirements
- Produce design solutions to meet user requirements
- Evaluate the designs against requirements.

If an appropriate plan of the human-centred design process is prepared initially and these stages are iteratively followed successfully, then the designed solution should meet the user requirements. The publications in this thesis focus on the first two stages of this process in particular: understanding context of use in order to specify appropriate user requirements.

Publication C provides further context for domestic energy demand, especially heating energy, and shows the role of the user perspective in this research area. The publication is based on research from the CALEBRE project (2008-2013), which also forms the research basis for publications F, G, H and I in the thesis. This project, jointly funded by the Research Councils UK Energy Programme and E.ON, aimed to establish a validated, comprehensive mechanism for reducing UK domestic carbon emissions within solid walled housing that is acceptable and appealing to users. This focus on user acceptability and appeal required a specific user centred approach, and allowed the author (who led the Workpackage in this area) and her colleagues to integrate user requirements into an otherwise largely engineering-driven project. Early findings from the CALEBRE householder study are included in publication C, including barriers to adoption of energy saving measures, which demonstrate the range of non-technical challenges facing technology developers.

Publication D presents a case study chapter that formed part of a larger report to UKERC (UK Energy Research Centre) on the future role of thermal energy storage in the UK energy system. The report considered the technical feasibility of thermal energy storage as well as exploring non-technical factors influencing adoption. This proved to be an area where there had been little previous research, as there are very few significant thermal storage systems in use in the UK and so the case study of Pimlico District Heating Undertaking provides an early insight into this area. The case study, based primarily on literature and interview data, collected by the author, further illustrates the range of social barriers to adoption of domestic energy demand reduction, and therefore the need to understand these in detail if future technology development and implementation is to be successful.

The domestic setting provides an added level of complexity when compared with commercial properties, where the majority of studies into human behaviour and energy use have been conducted. The essence of the house being a home, more than just a place to live, is critical, and bound up with this are the sentimental values people place on their home and the things within it. This means that methods that might be acceptable to use in offices are not suitable for the home. The line of enquiry may need to be more subtle and diverse, compared with a more standard post-occupancy evaluation that is commonly completed after commercial buildings are commissioned (e.g. Zimmerman and Martin, 2001; Cooper, 2001). Publication C explores the owner-occupier part of the housing sector. For owner occupied homes, of which there are 15 million in England and Wales (ONS, 2013), there is an added requirement to engage the homeowner in energy demand reduction, through the uptake of measures and any associated behaviour change. As owner occupiers, householders have to spend their own money on refurbishment or new technology, suffer disruption of some sort during the installation and live with the consequences. If these are positive experiences, then they are likely to continue to make improvements to their home. Negative or disruptive experiences will deter someone from taking further action. It is also common to see householders 'taking back' saved energy by increasing their comfort levels; by improving the efficiency of their home, they are then able to heat their home to a higher temperature for the same cost, resulting in little or no net saving in carbon (Hong *et al.*, 2006; Hong *et al.*, 2009; Sanders and Phillipson, 2006). In many cases, the improved comfort might only bring a household up to the expected levels of many (for example, if they were living in a previously cold house); however, this still does not contribute to meeting the carbon reduction targets.

The four publications, A, B, C and D, show how the topic of energy demand reduction is increasingly important in our changing society and use of technology, how domestic energy forms a large part of the use of energy and, importantly for this thesis, shows how user centred design can assist in understanding how domestic energy demand can be reduced. The initial findings in publications C and D show, in particular, the range of non-technical barriers to energy saving measures, illustrating the complexity of the context of use, and so underlining the importance of its understanding.

3 Enhancing engineering data in the understanding of domestic energy demand

The second research question asks how user centred information can enhance engineering data in the understanding of domestic energy demand; this is addressed in two parts. Publications E, F and G demonstrate, through a variety of methods, how user centred information can be collected and presented in a format appropriate for the engineering audience. Publications H and I provide examples of the integration of technical and user feedback in relation to two aspects of domestic energy demand reduction.

Publication E presents data collected as part of the Equipment Management Trial under The Application Home Initiative (TAHI) suite of projects, funded by the (then) Department for Trade and Industry, and which ran from 2002-2005. This multi-partner, multi-disciplinary project was dominated by technology specialists. The author led the Workpackage that related to users, but needed to convey to the project partners that people were unlikely to indiscriminately adopt the new smart home technology they were proposing as people had other values within the home. For example, whilst it was technically possible to produce a washing machine that could remotely provide data on the water temperature of the second rinse cycle, the need for this information was not evident. The research reported in publication E aimed, through a photo study, undertaken by the author and her team, to illustrate the breadth of things valued within people's homes and the variety of communication methods, information stores, time saving devices, etc, used at home. The purpose was to show technologists that they must take account of user needs in order to produce successful products, services and systems, at a time when smart home technology was emerging as a mainstream proposition. A novel 'Mission pack' was developed to collect the information from participants, developed in part by the author and based on Gaver's Cultural Probes (Gaver *et al.*, 1999). The collected data were then analysed through content analysis and illustrate that the development of future smart home technologies should carefully consider the users' needs. The subsequent CALEBRE project, which ran from 2008-2013, put user requirements at the centre of the research (see Figure 2, reproduced from Loveday *et al.*, 2011), as a result of the author's involvement from the outset of the

proposal preparation and the increasing awareness that user centred design was a valuable approach within energy demand reduction.
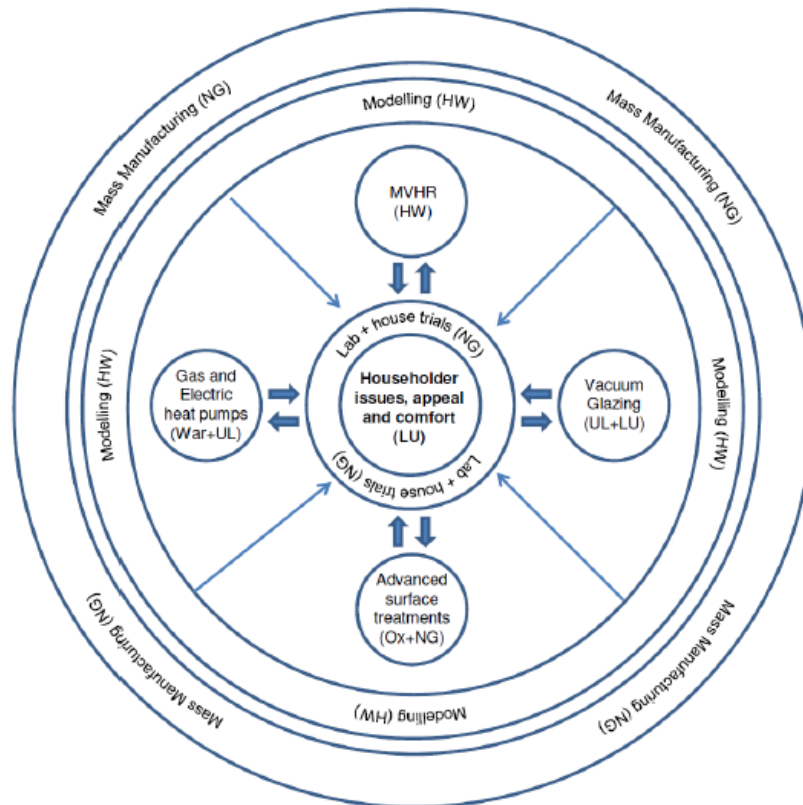
Key to figure:

HW = Heriot-Watt University   LU = Loughborough University   NG = University of Nottingham
Ox = University of Oxford   UL = University of Ulster   War = Warwick University

Figure 2. Project CALEBRE elements and teams, with the user centred issues at its heart (Loveday *et al*., 2011)

This focus on the user has been further evidenced by more recent calls for proposals from the EPSRC (Engineering and Physical Sciences Research Council) that require user centred design (under various names) to be an integral part of research in this area (see, for example, the End Use Energy Demand centres (total funding £43million from EPSRC, ESRC (Economic and Social Research Council) and industrial partners); four collaborative projects (2010-2012) funded by the Technology Strategy Board (now Innovate UK) and EPSRC (£2.3million) that aimed to explore how the demand for energy in non-domestic buildings could be reduced through encouraging changes in people's behaviour and by designing energy-related technology and services that are more user-friendly). The Technology Strategy Board's Chief Executive, Iain Gray, reports "*Technology on its own is not the silver bullet that will reduce energy consumption. The way that people interact with buildings, and how they understand*

and use the technology that is available, is a key factor. If technology designed to improve the energy efficiency of a building doesn't engage with the people who use it, then the building will underperform and energy savings will be limited. Buildings, and the technology within them, need to be 'user centred' in their design. These projects will help us to better understand user-building interactions and will provide opportunities to develop innovative products and services that will help to deliver a better working environment while lowering CO_2 emissions" (TSB, 2013). The importance of user centred design within research and development is clearly being realised.

Publication F includes data collection methods from the CALEBRE project, devised as part of a research student programme (Mallaband, 2013) and supervised by the author. The data were further analysed by the author and considered in the context of a practice-orientated approach, a growing theoretical framework in the area of energy demand reduction research which focuses on the routines, habits, conventions and conceptions of normality (Shove, 2003). The research described in the publication is considered in terms of how well it met the challenges presented by the technologists on the multidisciplinary CALEBRE project, using windows and glazing as a case example. The use of practice theory as the lens by which home improvement is considered provides a perspective on the 'one-off' acts of consumption of installing a new boiler, loft insulation, double glazing etc. Whilst practice theory more commonly considers more frequent energy using practices such as laundry or bathing (Gram-Hanssen, 2007; Kuijer and de Jong, 2011; Shove, 2003), its relevance to these occasional activities is reflected upon in the paper. Publications F and G focus particularly on the practice of home improvement as a way of exploring how new energy saving technologies might be introduced into the home. Many home improvements include an element of energy demand, sometimes reduction (for example, through the installation of loft insulation, double glazing or fitted carpets), sometimes increasing (for example, a higher capacity boiler or larger radiators to keep a house warmer). This topic is explored further in publication G, which includes a review of literature around home improvement, before developing a set of home improvement personas to articulate a set of possible target users to technology developers, designers, engineers and policy makers. This provides user centred information in a format appropriate to the target audience, essential to good user centred design.

Publication H describes combined research from Heriot Watt University (modelling) and the author (householder preferences and practices) into airtightness in homes, focusing on the problems with achieving airtightness in practice and the preferences from homeowners of older homes to retain particular features of the house that reduce airtightness, for example open fireplaces and original windows. This gives a better understanding of how people use (and waste) energy at home and the magnitude of that use. Publication I reports findings from temperature loggers in homes, coupled with comments from a diary study from the homeowners about the thermal conditions in their homes. This provides qualitative insights alongside the quantitative data, to attempt to explain why temperatures in these homes were lower than average, providing a deeper understanding of the complexities of heating a solid walled home. The quantitative data alone might provide information that is misleading – that an average living room temperature of less than 18°C is desirable – but the qualitative information provides some explanation that, for example, the desire to retain traditional features of the home (single glazed windows, for example) perhaps limits the temperature that can be achieved and dictates the heating system potential. Only by providing these types of data together can the technologists, designers, engineers and policy makers become aware of the strong influence of the human factors and so ensure that future designs are effective from both a performance and user centred perspective.

4   Personal contribution to the publications

Many of the publications presented in this thesis are the result of a team of individuals, working collectively on major projects and small studies. The publications that do not relate to PhD research (publications A, B, C, D and E) are the result of the author's involvement in research projects in the area over the past 12 years. Some publications are based on data collected as part of other people's PhD research (all but one supervised by the author), but include significant additional analysis (publication G) or a focus on data that were not included within the research students' theses (publications F, H and I). As a result, whilst the students' work contributed to the publications, the contributions claimed here are original. Table 1 identifies the contribution to each publication from the author of this thesis. The contribution of the knowledge to the overall research aim is detailed in the final section of this chapter.

Table 1. Publications and the author's contribution

Publication	Author's contribution to the publication
Publication A - Peer-reviewed journal paper Loveday D, Bhamra T, Tang T, Haines V, Holmes M and Green R (2008). The energy and monetary implications of the '24/7' 'always on' society. Energy Policy 36(12) 4639-4645	Co-author; review of the topic, in particular the sections on social and technological change; shared identification of the role of design, energy management and technology; contribution to the structure of the paper. Approximate overall contribution: 15%
Publication B - Editor-reviewed book chapter Haines V and Mitchell V (2013). Intelligent energy saving the home: A user centred design perspective. In: Intelligent Buildings: Design, Management and Operation (2nd Ed). D Clements-Croome. (Ed). London: ICE Publishing	Lead author; review of relevant literature and lead editor of the material; development of the structure of paper. Approximate overall contribution: 65%
Publication C - Organising committee-reviewed conference paper Vadodaria K, Loveday D, Haines V, Mitchell V, Mallaband B and Bayer S (2010). UK Solid-Wall Dwellings - Thermal Comfort, Energy Efficiency Refurbishment and the User Perspective - Some preliminary analysis from the CALEBRE Project. Adapting to Change: New Thinking on Comfort. Cumberland Lodge, Windsor, UK, 9-11 April 2010. London: Network for Comfort and Energy Use in Buildings, 1-16	Co-author; provision of research direction for the study reported; method development support; some data collection; supervision of research student undertaking the data collection and analysis; input to the paper preparation. Approximate overall contribution: 30%
Publication D - Peer-reviewed research report Haines V (2014). Case Study 2: Exploring the non-technical barriers to UK deployment. In: The future role of thermal energy storage in the UK energy system: Assessment of technical feasibility and factors influencing adoption. Eames P, Loveday D, Haines V and Romanos P (2014). UKERC Research Report	Sole author of the case study chapter; review of literature and conduct of interview / visit to the case study site. Overall contribution: 100%
Publication E - Peer-reviewed journal paper Haines V, Mitchell V, Cooper C and Maguire M (2006). Probing user values in the home environment within a technology driven Smart Home project. Personal and Ubiquitous Computing 11(5) 349-359	Lead author; project workpackage leader; study design development; shared data collection and analysis; lead on the paper preparation. Approximate overall contribution: 35%

Publication	Author's contribution to the publication
Publication F - Peer-reviewed journal paper Haines V, Mitchell V and Mallaband B (2012). Merging a practice-orientated approach with an engineering-driven product development: A case study on home improvement. Journal of Design Research. Special issue on Design, Sustainability and Behaviour, 10(1/2) 28-49	Lead author; project workpackage leader providing research direction for the study reported; method development support; some data collection; supervision of research student undertaking the data collection and analysis; lead on the paper preparation. Approximate overall contribution: 40%
Publication G - Peer-reviewed journal paper Haines, V and Mitchell, V (2014). A persona-based approach to domestic energy retrofit. Building Research & Information, Special Issue: Energy retrofits of owner-occupied homes, 42(4), 462-476	Lead author; project workpackage leader providing research direction for the study reported; method development support; some data collection; supervision of research student undertaking the data collection; shared analysis of the data and development of the personas; lead on the paper preparation. Approximate overall contribution: 55%
Publication H - Peer-reviewed journal paper Banfill P, Simpson S, Haines V and Mallaband R (2012). Energy-led retrofitting of solid wall dwellings – technical and user perspectives on airtightness. Structural Survey: Journal of Building Pathology and Refurbishment, 30(3) 267-279	Co-author; paper reports a combination of two project workpackages - lead in one; research direction for the householder study reported; method development support; some data collection; supervision of research student undertaking the data collection; analysis of the data; lead on the user centred aspects to the paper. Approximate overall contribution: 25%
Publication I - Peer-reviewed journal paper Vadodaria K, Loveday D and Haines V (2014). Measured winter and spring-time indoor temperatures in UK homes over the period 1969 to 2010: a review and synthesis. Energy Policy 64, 252-262	Joint supervision of the research student whose work forms much of this paper; analysis and reporting of the user centred data and contribution to the paper preparation as a whole. Approximate overall contribution: 20%

5   Research methods employed

A range of user centred research methods has been undertaken in the preparation of the publications forming this thesis, in both the collection and analysis of the data. In order to determine the appropriate choice of method or suite of methods for each study, the key research questions to be answered by the study were first identified. From these, specific and more detailed questions were developed that related to the overarching research question. For each of these, a further consideration was made of whether the question

could be answered factually and simply, and therefore be suitable for investigation by a method such as a survey or simple interview, or whether a more significant depth of response was likely, and so require a more probing approach. The required context for each approach was also considered; could the data be collected remotely, in a neutral location or was investigation in context within the home essential? Once these factors had been determined, the possible approaches that might enable the required type of data to be collected were identified from the author and her colleagues' 'toolkit' of methods, developing new methods where there was no appropriate approach available. A key criterion for any method was that it was interesting and engaging to the participant; collecting data from householders requires some sort of invasion into their personal space and so any approach must ensure that the householder feels in control of the information they provide and, critically, enjoy taking part in the research. The various methods used in the research underlying the publications in this thesis are described in the following sections, then later summarised, including identification of the author's contribution, in Table 2.

5.1 Data collection

Using primarily qualitative methods, the author has attempted to develop an understanding of user requirements in the field of domestic energy research. Publications A and B primarily draw upon reviews of the literature, grounded in the author's general research experience. Publications C, F, G, H and I report different aspects of a major householder study from the CALEBRE study, which used a multi-stage, mixed methods approach, as outlined in publication C:

- Visit One – A face to face, in home, one to two hour semi-structured interview, to understand people's motivations and experiences with home improvements, exploring issues of disruption, cost and service provision.
- Between Visits One and Two – A comfort diary, developed by one of the author's PhD students (Mallaband), to collect data about times when householders felt thermal discomfort and their reasons why this might be. Temperature and relative humidity data loggers were placed in two rooms in each home to record data that could be associated with the subjective reported data.
- Visit Two – A face to face, in-home, one hour semi-structured interview, to explore with householders the consumer appeal and practical acceptability of specific

CALEBRE technologies. This included gathering data on architectural features of the home that might impinge on retrofitting, or space limitations to prevent installation of interventions.

- Visit Three – An assessment of the home to generate an Energy Performance Certificate (EPC). This was conducted by another of the author's PhD students (Vadodaria) who also worked on the project.

Publication D explores a case study through the use of a semi-structured interview with the engineers who managed the system and tour of the site. Interview questions, based on the limited literature available and the author's experience of domestic heating systems, allowed for an understanding of the district heating system, the role of the thermal energy store and the implications of the system for the householders. Whilst an interview guide was developed, the conversation was more informal, often led by the engineers providing information as it came to them, with the guide used at the end to check all the salient points had been covered (Robson, 2011).

Publication E used a 'Mission pack' to take the participants through a set of tasks in a structured way. Based loosely on the approach of Gaver *et al.* (1999), each task required participants to identify (and photograph) items according to a theme, adding comments for their reasons. The purpose of structuring the tasks as Missions was to ensure the participants completed them in the prescribed order (Mission One, then Mission Two etc). This meant that participants were not influenced by the later activities. This was particularly important for the early tasks which asked people to identify things around the home that were of value to them, were used to communicate, store information etc; the final tasks focused on technology. Had these been earlier, it was anticipated that the participants would have been influenced by this and so given more technology-focused examples for the other questions. As technology potentially can be something people value, used to store and communicate information (even in 2005 when the study was completed), this may have created bias in the results. As it was hypothesised that people might value and use a variety of items around the home that are not necessarily technology-based, the sequential Mission tasks ensured that people were not influenced one way or the other in the early tasks.

5.2 Data analysis

Interview data from the CALEBRE householder study were transcribed and analysed in NVivo by the research student supervised by the author. Using a thematic analysis approach (Braun and Clarke, 2006), key barriers and motivators to home improvement were identified through inductive discovery (Gray, 2014:16), which are reported in publications C and F. Interview data from the case study in publication D were also transcribed and analysed for emerging themes, but the significantly smaller volume of data meant that this could be done without using NVivo and was completed by the author.

Publication G describes the process to develop a set of personas based on Goodwin's (2010) approach. The use of personas to articulate more clearly a set of possible target users provides a way of presenting user centred information in a format that is of relevance to other disciplines. The personas were based on the householder study from the CALEBRE project, but the author, with her co-author, significantly developed these data further to create the personas.

The author's individual contribution to the methods and analysis approaches, for each publication, is identified in Table 2, overleaf.

Table 2. Research methods used in the underlying research for the publications

The author's contribution to the research methods is indicated as follows: Full contribution in **bold**; shared contribution in black; supervisory contribution in grey.

Publication	Data collection methods used	Data analysis methods used
Publication A Loveday *et al.* (2008)	Literature review in particular the sections on social and technological change, and the role of design, energy management and technology	
Publication B Haines and Mitchell (2013)	Literature review across the topic	
Publication C Vadodaria *et al.* (2010)	Visit 1: semi-structured interview and home tour Comfort diary and temp/RH data loggers Visit 2: semi-structured interview Visit 3: EPC assessment	Full interview transcription Thematic analysis using NVivo Identification of the key barriers and motivators
Publication D Haines (2014)	**Literature review and site visit, including semi-structured interview**	**Thematic analysis**
Publication E Haines *et al.* (2006)	Mission packs	Content analysis of the photographs, with reference to the descriptions provided by participants
Publication F Haines *et al.* (2012)	Visit 1: semi-structured interview and home tour Visit 2: semi-structured interview	Full interview transcription Thematic analysis using NVivo Identification of key challenges and responses to these **Glazing examples**
Publication G Haines and Mitchell (2014)	Visit 1: semi-structured interview and home tour Visit 2: semi-structured interview	Development of personas **Application of the personas to solid wall insulation example**
Publication H Banfill *et al.* (2012)	Visit 1: semi-structured interview and home tour	**Analysis of relevant practices relating to airtightness**
Publication I Vadodaria *et al.* (2014)	Comfort diary and temp/RH data loggers	**Analysis of comfort diaries**

6   Achievements of the research

This thesis presents nine publications that, as a collection, show how the author has introduced a user centred design approach to enhance the understanding of domestic energy demand reduction into an engineering-dominated domain. This collection of publications shows how user centred design can contribute towards a better understanding of people and their use of energy within the home. In particular, it illustrates ways in which user centred data can be introduced into an engineering domain so as to provide a complement and enhancement to the body of knowledge. However, it is important to remember that the application of user centred design to energy demand reduction is a recent activity, led in part by the author's research and the publications included here. The central focus on the user within the CALEBRE project arose directly from the author's learning from the TAHI project and involvement in the CALEBRE project proposal team. Its continued application in other projects has resulted from the author and her co-authors' activity in this area, working with engineers to find solutions that reduce energy demand <u>and</u> meet the needs of the user. Hewitt (2012) highlights that technological interventions must be "*acceptable to the user in terms of minimal disruption during installation, ease of use and alignment with lifestyle expectations.*" As energy demand reduction is a socio-technical problem (Lomas, 2010), the successful integration of user centred information is essential. However, interdisciplinary working in domestic energy demand reduction is in its infancy, and successfully combining user centred understanding with technical data in this field is still developing. This thesis contributes to the understanding of how this can be done.

As a reminder, the aim of the thesis is to identify how qualitative information about users' experiences, values and practices relating to UK domestic energy demand reduction can be collected and presented effectively to an engineering audience and incorporated into engineering-focused research. Two research questions were asked at the outset of this research:

1. Why is an understanding of user requirements important to domestic energy demand reduction research?

2. How can user centred information enhance engineering data in the understanding of domestic energy demand?

The first question is answered through the wide and unusual range of information that people provide about using and saving energy in their home. The publications presented here contribute to knowledge about why and how people make improvements to their homes, the types of people that might take on an energy saving retrofit, the range of non-technical barriers to domestic energy storage, the human factors that contribute to people's dislike of an airtight home and reasons why some householders might tolerate a thermal environment that is less than ideal, by exposing the wider factors that motivate people's behaviours and attitudes. People contribute significantly to the use of energy in the home and so it is imperative that an understanding of the human dimension is included in energy research. This is reflected in the increase in research calls that require both behavioural AND technical expertise in combination; truly integrated interdisciplinary research.

The answer to the second question, asking how user centred information can enhance engineering data in the understanding of domestic energy demand, is illustrated through the publications in this thesis. These papers show how a user centred design approach can contribute to the understanding of human factors at a number of levels, from background and awareness raising to user characterisation. The next step is to apply this user information in engineering models of domestic energy, so that more representative, evidence-based models can be created, to more accurately inform the predictions of energy demand. This final stage is not illustrated within the publications in this thesis, but form future research objectives. Providing information about users to engineering colleagues at the appropriate time is also important. The research presented here has progressed over the past decade, such that the early publications in this thesis (A from 2006 and E from 2008) provide more general insights into their respective topics as a whole. For sectors where there is little known, then a raising of awareness of the human factors issues is sufficient to ensure that technical solutions do not completely ignore the needs of the user. As engineers can often focus their attention on producing a technical solution that actually works, the consideration that it needs to be usable and appealing to the consumer is far removed from their immediate objectives. However, providing information about the end user was described as a "*reality check*" by one engineer working with the author; it made him realise that his technical solutions may not be acceptable to the consumer. Research into domestic energy use has grown in volume and scope in recent years and so more

detailed understanding is now needed – and more sophisticated outputs required. The creation of the personas (publication G) and the interdisciplinary outputs of publications H and I show how the author has integrated knowledge about householders into a form that can be used by engineers. The evidence-based data provides the robustness required by the engineer to support the development of a new product or the simulation of a system that includes an aspect of human behaviour. The user centred research within these latter papers may still only be based on small sample sizes or be more limited in scope, but this still provides a very useful and relevant contribution to the research topics. The different roles are categorised in Table 3.

Table 3. The role of user centred design in domestic energy demand reduction research

Role	Contribution	Engineering application
Background and awareness raising	Demonstrating that users are important in the system, but the level of detail required is limited and the robustness of the information may be low – case studies provide effective sources of data	Early exploration of the technology in practice. Providing early warning that a technological solution may need to take account of (often unanticipated) user requirements
Contextual understanding	Providing more detailed understanding of the context of use within people's homes relating to energy use and demonstration of the range of activities, experiences and motivations/barriers around people's behaviour	To provide engineers with detailed awareness of the range and complexity of domestic energy demand. These provide the reality check needed to ensure the engineer thinks about the householder and has data to support their decision making
User requirements specification	Specific requirements that can be incorporated into design specifications, so that the range of user needs are included within the development of a technology	To provide the developers of energy saving technology with specific design requirements that incorporate the needs of users, in a form that is familiar
User characterisation	Development of evidence-based, detailed descriptions of householders, such as personas, that can be used to define or characterise the user	To provide details about a specific target user in a form that is easily understandable and conveys the key aspects of the characteristics of particular user types
Application of user information into engineering models	Taking the user characterisation information to create representative user models, providing an integrated, evidence-based understanding of people within engineering models	To allow engineering models to more accurately represent the behaviour of real householders and evaluate the effects of people within the system

The research methods that underpin the publications in this thesis are familiar to those working in the human sciences. Their application within engineering projects is more recent and, within the domestic energy field, is part of the contribution of this thesis. In particular, the methods developed to obtain the user requirements of householders constitute innovations and contributions to knowledge in user centred design.

In some application areas, such as thermal energy storage, there has been very little research in the UK to date that considers the requirements of people and so the research in publication D presented in this thesis was exploratory and sample size limited due to the small numbers of case studies in the UK. However, in combination with the technical exploration in the wider report (Eames *et al.*, 2014), this provides a valuable perspective to the engineers. The more recent publications F, G, H and I (from 2012 and 2014) provide more focused findings, on a specific part of the domestic sector – owner occupiers in solid wall houses. An awareness of the importance of understanding user requirements was already established by the author in the development of the research programme and so these publications provide an applied understanding of householders.

Collecting and analysing qualitative data from householders is a time consuming activity; when this is combined with technical monitoring of the homes, the complexity is significantly increased and hence only small scale studies have so far been conducted in the UK. Projects such as IDEAL[1] and DEFACTO[2] (for which the author is a Co-Investigator) are attempting to investigate energy demand in homes at scale (looking at hundreds of homes), but even these are not likely to be statistically representative of the UK population or housing stock. Publications in this area, including those in this thesis, are therefore typically only case study examples or based on a limited sector of the population. Over the next decade and beyond, it is anticipated that projects investigating domestic energy demand reduction will involve longitudinal, large scale demonstrators, collecting a fully integrated combination of social and technical data.

[1] IDEAL: Intelligent Domestic Energy Advice Loop Project (2013-2017). Led by Prof N Goddard, University of Edinburgh, EPSRC grant number: EP/K002732/1

[2] DEFACTO: Digital Energy Feedback And Control Technology Optimisation Project (2012-2017). Led by Prof K Lomas, Loughborough University, EPSRC Grant number: EP/K00249X/1

The papers presented here have a UK focus, as that was the geographical arena for the research; however, the approaches described here can be, and are already being, transferred to other populations, within the author's ongoing research, exploring domestic energy demand around the world. This thesis shows how user centred design can offer an approach for that continued research.

This thesis has positive implications for the future of user centred design and for people working across domestic energy demand reduction. User centred design can play an increasingly significant role within cross-disciplinary teams, providing a bridge between end users and engineers. This will provide a more detailed understanding of the actions of householders within domestic energy demand research, help to provide more accurate representations of behaviour within engineering models and ensure that people are considered in full within the complex domestic energy system. The value of user centred design is starting to be recognised within this field, but needs further promotion to raise its profile alongside the broader range of social science disciplines. The publications presented here demonstrate how user centred design can add value to an engineering-driven research area by collecting and providing information in a format that is useful to others in the field. By providing a deeper understanding of the context of use and developing user requirements that can be considered within the development of energy saving technology and policies, a more acceptable and desirable outcome is possible. In order for the research community to tackle the wicked problem that is domestic energy demand reduction, and the wider carbon reduction targets, it is essential for all factors to be considered, including the human.

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PUBLICATION A

Loveday, D.L., Bhamra, T., Tang, T., Haines, V.J.A., Holmes, M.J. and Green, R.J. (2008). The energy and monetary implications of the '24/7' 'always on' society. Energy Policy 36(12) 4639-4645.

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Abstract

This paper reviews the trends in society, technology and energy demand of the past 30 years, together with the growth of the 'on-demand' culture. The '24/7' or 'always on' society can be defined as one where people demand - and generally receive – what it wants 'now'. It has grown up in parallel with developments in information technology, which have produced the services needed to meet that demand. Larger numbers of appliances, resulting from greater affluence and disposable income, have increased energy use, despite energy efficiencies in other areas. Whilst monetary factors suggest that changes brought about by the 24/7 society will generally be self-correcting at the macro-economic level, there will nevertheless be individual effects for individuals, such as potentially severe impacts on the fuel poor as electricity prices rise.

We conclude with a view of future directions. As the 24/7 culture continues to grow, there is scope for designers and for information technology to manage and reduce energy consumption. This includes buildings, their services systems, and the mix of new technologies that will be deployed over the next twenty years or so, including the possibilities for data exchange and control at the interface between energy suppliers and consumers, coupled with greater understanding of the behaviour of the consumers themselves.

1 Introduction

In 2003 a survey carried out by Yellow Pages (2003) attempted to identify changing attitudes to modern lifestyles. People aged 22 to 44 were asked what 24/7 (24 hours per day, 7 days per week) goods and services they would most like to see available in their area. The most requested round-the-clock service was healthcare, with just under two thirds of people wanting to be able to contact their doctor, dentist or local pharmacy at any time day or night.

Interestingly, in this survey entertainment is not mentioned. But if asked to provide a definition of a 24/7 society many of us would provide examples related to leisure and convenience, perhaps television and radio programming, satellite television services, such as

'on-demand' TV, computer access to the internet and email, call-centre services for banking, mail-order shopping and 24-hour shopping at supermarkets. These are the services that affect the everyday lives of people in the UK and other Western societies, and this review will focus on these in terms of likely energy and monetary implications. This example might suggest that the real issue is not a 24 hour lifestyle – everybody needs to sleep – but a society that requires what it wants 'now'. If this definition is accepted, then it is necessary to examine the changes in our society and the impact of these changes on energy use and hence carbon emissions.

Most energy consumption in the built environment occurs in the domestic sector. A smaller, yet significant, amount of energy is consumed in office buildings, many of which will now be operating for far longer than the conventional '9 to 5' day. If it is also accepted that many longer working days will be spent 'at home', then, in order to understand the impacts of changes in our society's attitude to work and leisure, it is reasonable to focus on what is happening on the domestic scene. In this context Moll *et al.* (2005) identify households rather than individual consumers as the principal determinant of resource consumption; in addition, they identify the household as a social decision-making unit. They estimate that 70-80% of national energy use and greenhouse gas emissions may be related either to household activities directly or to activities required to deliver goods and services to households and to manage the waste flow they generate (Moll *et al.*, 2005).

To address these issues, the paper is structured as follows. First, there is a short review of how society has changed over the last 30 years from the perspective of technology, energy demand, and the growth of the 'on-demand' culture, together with the manner in which these inform our current situation. Monetary implications are then discussed, followed by a view of likely future developments in terms of the roles that design and information technology might play in shaping future energy demand.

2 What has changed?

In this section we look at changes in energy use, how society has changed and the technological changes that allow the 'on demand society' (see Table 1).

Table 1. Direct energy demand including heat and electricity since 1970s

	Space heating	Water heating	Appliances and Lights	Data source
Energy carriers	Coal, oil, coal gas Natural gas		n/a	Van der Wal and Noorman 1998
	1950, 90% of UK's total primary energy was supplied coal; 2003, 80% of homes used natural gas as heating fuel			DTI (2004) in: Environmental Change Institute (2005)
Percentage of residential delivered energy consumption (electricity and gas)	77%		23%	Environmental Change Institute (2005)
	60%	20%	20%	Design Council (2005)
	59%	24%	17%	DTI (2002) in: Energy Saving Trust (2006b)
Change in demand / **Total**	Increased 36% (1970-2001)		Increased 70% (1970-2001) Increased 123% (1970-2003)	1970-2001 Environmental Change Institute (2005) 1970-2003 Environmental Change Institute data in: DTI (2003)
Change in demand / **Per household**	Remained stable (1970-2001)			
Determinate of Change	Increasing No. of households		Increasing income	Van der Wal and Noorman (1998) Environmental Change Unit (1997)
	Low energy prices		Low electricity price	
	Availability of central heating system		Availability and purchase of domestic appliances	
	Insulation installed in dwellings		Energy use of per appliance	
	Higher indoor temperature		Use patterns	

Energy use for domestic space heating increased by 28% between 1970 and 2005. In the same period, energy use for lighting and appliances increased by 148% (DTI, 2006). The increase in energy use for space heating can be attributed to increased average household temperatures, 12°C in 1970 and 18°C in 2002 (Utley & Shorrock, 2006). According to the Energy Saving Trust (2006a), 22% of people in the UK turn up the thermostat instead of putting on extra clothing.

Increases in energy use can also be attributed to the number of households, which has risen significantly over the last 30 years whilst the population has remained relatively stable (see Figure 1).
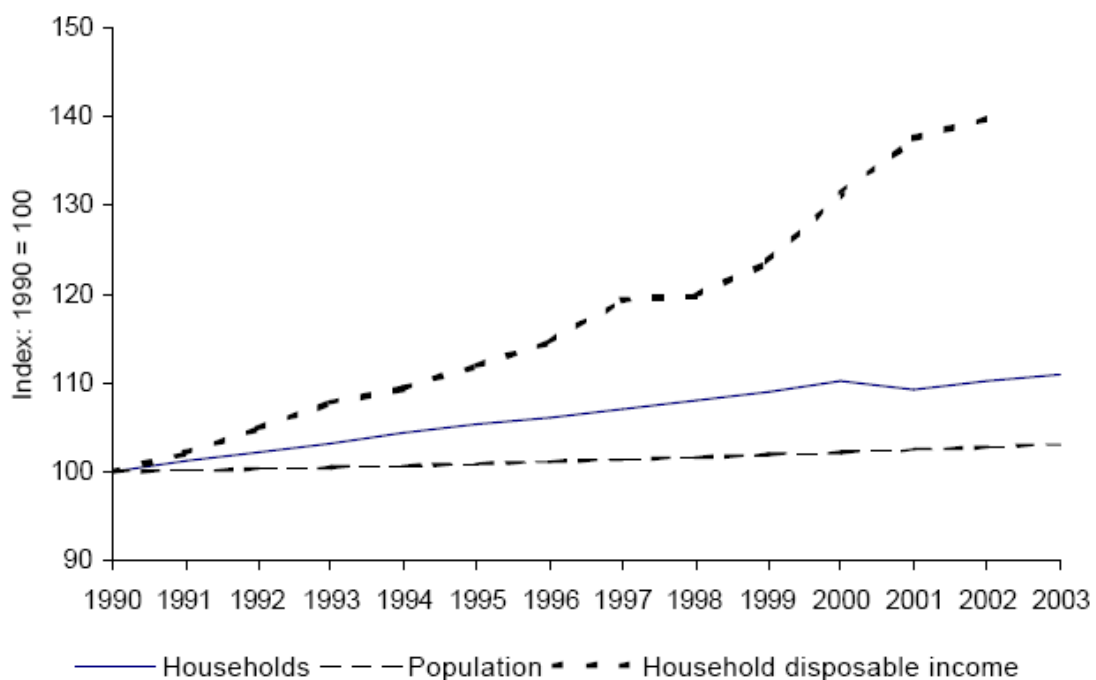
Figure 1 Population, Households and Disposable Income Changes (Source: DTI, ONS in BERR, 2007a)

2.1 Social change

2.1.1 Demographics

Demographic changes have influenced appliance and residential energy consumption (Environmental Change Institute, 2005; Moll *et al.*, 2005; Van der Wal and Noorman, 1998; Van Diepen, 1998). The divergence between the growth of the population and the number of household indicates that the average size of the household decreased from 3.0 in 1961 to

2.4 in 2004 and is currently 2.3 (Jefferies, 2005). Only 7% of households in the UK contained more than four people in 2002 compared to 14% in 1971, and the proportion of single-occupancy dwellings rose from 12% to 29% over the period of 1961 to 2004 (Environmental Change Institute, 2005).

There are also more single-generation households; young people leave their parental home sooner and the elderly live by themselves and not in extended families. Divorces also add to this number (Sanne, 2002). According to Van Diepen (1998), the UK is rather unusual in that the number of households increased much more rapidly than the population.

The trend in household numbers and size is a key factor of energy consumption since each household requires its own set of appliances and lights (Environmental Change Institute, 2005) and within the household each member expects a TV set, computer or telephone (Van Diepen, 1998).

2.1.2 The '24/7' Society

There is some evidence that householders stay up later to use 24 hour services: 7 million people (one seventh of the UK adult population) undertake economic activity between 6pm and 9am, with call centres experiencing high volumes of calls in the early morning (Hicks, 2006).

Sleep time has reduced from 508 minutes in 2000 to 491 minutes in 2005 (Office for National Statistics, in BERR, 2007a). Night-time is no longer ring-fenced for sleep. It has become the new daytime, offering us the chance to catch up on everything we did not manage to cram in during what used to be our waking hours. Now, instead of sleeping, we can check our bank balances by phone, buy groceries, surf the net for cheap flights or swap our slippers for training shoes and go to the gym.

Research carried out by the Future Foundation (2003, in Hicks, 2006) argues that the increase in '24/7' culture is being driven by rising affluence and disposable income of those in higher earnings brackets who want to enjoy the fruits of their labour. The Future Foundation study found that two thirds (67%) of people think that supermarkets opening 24

hours a day is a positive trend – indeed the study suggests that 15% of shopping takes place between 6pm and 9am.

Research by Shell estimates that in the UK, up to 17 million people regularly shop at night, and Nielsen Homescan found that 58% of young people with no dependents would shop at night if amenities were readily available (both quoted by Kreitzman, 1999, in Geiger, 2007).

2.2   Technological change

Since 1970, homes and products have become more efficient. But the increasing numbers of products and the advanced technological innovation they contain have brought a sharp rise in the domestic energy consumption. According to data from the Environmental Change Institute, UK residential electricity demand doubled from 44TWh to 89TWh between 1972 and 2002 (Energy Saving Trust, 2006b). Table 2 provides a breakdown of the electrical usage in dwellings. The items by an asterisk are those that would have been common in the 1970s.

Table 2. Domestic energy and electricity usage broken down by sector (Environmental Change Institute data in: DTI, 2003; Energy Saving Trust, 2006b:13-17)

Sector	% Energy usage	%Electricity usage	Appliance	Penetration
Space heating	59%			
Water heating	24%			
Cold	3%	18%	Fridge-freezer	64%
			Refrigerator*	43%
			Upright freezer	27%
			Chest freezer	17%
Wet	2%	14%	Washing machine*	79%
			Tumble dryer	40%
			Electric shower	35%
			Dishwasher	25%
			Washer dryer	15%
Cooking	3%	17%	Kettle*	97%
			Microwave	83%
			Oven*	80%
			Electric oven*	59%
			Electric hob*	46%
			Deep fat fryers	34%
			Sandwich toaster*	33%
			Slow cooker	20%

			Cooker hood	18%
Lighting	3%	20%		
Consumer electronics	4%	21%	TV*	98%
			Cassette player/radio*	95%
			Hi-fi*	94
			VCR	87%
Miscellaneous	2%	10%	Personal care product*	94% (hair care)
			Mobile phones	81%
			Heater	80%
			DIY equipment	59%
			Computer	45%
			Monitor	45%
			Printer	32%
			Fax/scanner	11% (fax)
			Vacuum cleaner*	
			Home security system	
			Telephone/answer machine	

Ownership of home computers has increased from 0% in 1981 to 67% in 2005 (Market Transformation Programme, 2006). Daily use of the TV has increased by 13% between 1995 and 2005 (Boyny, 2006). It is estimated that standby energy consumption accounts for about 1% of domestic energy use in the UK, equivalent to 6% of domestic electricity consumption.

2.3   Energy Use

At the household level, the efficiency of buildings, heating systems and household appliances use has improved by around 2% year on year since 1970 (Energy Saving Trust 2006b). But increased use of appliances (see Table 2) and liking for warmer houses has swallowed up the hard-won energy gains. The energy supply requirement of the residential sector has increased by 32%. Electricity consumed by household domestic appliances and lights has increased by 70% (Environmental Change Institute, 2005) and is anticipated to rise by a further 12% by 2010 (Energy Saving Trust, 2006b).

Table 3. Estimated standby consumption by domestic appliances, 2006 (Market Transformation Programme, 2007)

Appliance category	Standby Power (Watts) mean	Stock (million units)	Standby time (hours/day)	Energy use (GWh)	Cost (£ million)
Desktops	3.4	23	13.7	392	39
Laptops	1.3	4	14.3	32	3
PC monitors:					
CRT	2.1	8	13.7	91	9
LCD	1.1	15	13.7	90	9
Plasma	4.0	0.1	13.7	3	0.3
MFD:					
MFD Inkjet	4.1	4	18.0	106	11
MFD Laser	10.0	0.1	18.0	6	1
Printers:					
Ink	1.5	9	19.1	102	10
Laser	14.2	2	13.1	161	16
Photo	1.9	2	11.6	16	2
Televisions:					
CRT primary	2.6	21	10.5	320	32
CRT secondary	2.6	32	12.9	583	58
LCD Primary	2.7	2	10.5	24	5-2
LCD secondary	1.8	4	12.9	32	3
Plasma Primary	4.0	3	10.5	46	5
Projection primary	1.8	2	10.5	10	1
DVD Player	1.9	23	9.1	491	49
DVD recorder	9.4	2	9.1	78	8
VCR	4.0	19	9.1	324	32
DTR	6.2	0.1	9.1	2	0.2
Mobile phone charger:					
3.5W	3.5	10	10.0	123	12
1W	1.0	60	10.0	220	22
Set-top boxes:					
Cable	15.2	2	7.0	124	12
Satellite	15.0	8	7.0	412	41
Terrestrial	6.4	8	7.2	194	19

There is little official historical information available on energy use by different types of consumer at specific times of the day. Between 2001 and 2007 electricity use between midnight and 5am increased by 10.9% in the summer and 14.5% in winter (National Grid,

2002, 2007). However, at the same time, daytime (8am-6pm) electricity use increased by 14% in the summer, and 11% in the winter (National Grid, 2002, 2007).

Internet businesses claim to be more energy efficient than conventional ones; Amazon.com, for example, uses only 6% as much energy per square foot to sell a book than a regular store (Abukhader & Jonson, 2003). However, estimates of electricity used to operate internet routers, switches and computers range from 1% to 8% of total US energy use (Abukhader & Jonson, 2003). Reijnders and Hoogeveen (2001) found that internet businesses may use less energy than other organisations to distribute goods, but that they electricity used in the computers of people buying on the internet may far outweigh these gains. In general, among several pilot studies and reports, we find a common view that there is no conclusive evidence that e-business and internet use have either increased or decreased environmental impacts, as there are examples of both positive and negative effects (Fichter, 2001).

3 Monetary Implications

The most obvious result of these changes is that people will be spending more money on electricity. Domestic consumers bought 116 TWh of electricity in 2006, at a cost of £11.8 billion (BERR, 2007b, Tables 1.7 and 5.3). The standby consumption depicted in Table 3 comes to just under 4TWh/year, with an estimated cost of almost £400 million/year. The total spending depends on both price and quantity, of course, for spending in 2005 was only £8.8 billion. Domestic electricity prices were 22% higher in 2006 than in 2005, on average, and this price rise contributed to a small fall in the volume of electricity consumed.

We might ask whether electricity consumption, and particularly increasing electricity consumption, will be affordable. Total consumer expenditure in 2006 was £794 billion, and the spending on electricity came to only 1.5% of this. For the average household, there is clearly scope for the amount spent on electricity to continue to rise. A substantial minority of households is fuel poor, however – the official definition is that they are spending more than 10% of their disposable income on heat and light. In 2005, 2.5 million households were fuel poor, and 2 million of those were vulnerable; that is, they contained children, or people

who were elderly, sick or disabled. Fuel poor households may be relatively less likely to own the modern appliances contributing to increasing electricity consumption. But any price consequences of that increasing consumption will have particularly severe impacts on the fuel poor.

We should ask why increasing electricity consumption might affect electricity prices. The good news is that if the existing networks are able to effectively distribute the increasing volumes of power, their fixed costs can be spread over a larger output, reducing the cost per unit distributed, and tending to lower prices. Of course, if the networks are not able to cope with increasing loads, more investment will be needed, with associated costs. The bad news is that, for a given stock of power stations, higher electricity demands will mean higher prices in the wholesale markets, and these will be passed on to consumers. In the longer term, rising demand would give generators the incentive to add more capacity, muting the impact on prices. But if the only way of accommodating the extra capacity is to use less suitable sites, costs will be higher, and the market will only regain its equilibrium at a higher price level. This could be a particular issue for renewable generators, where site-specific factors have a very significant impact on output, and hence costs per unit generated. Consumers will pay more, and the existing generators will make more money. Finally, if there is a fixed carbon budget, an increase in electricity output is only possible if the carbon intensity per megawatt hour falls, requiring more use of low-carbon generators. This must involve higher costs, since if the low-carbon generators were cheaper than high-carbon alternatives, they would be used, whether or not carbon emissions were important.

This leads us to consider the effects in the wider economy. The extension of Sunday trading hours provides a natural analogy to the 'always on' society. A study commissioned by the Department of Trade and Industry in 2006, when an extension was being considered, provides an estimate of the impact (Indepen, 2006). Large retailers' unit costs would fall by 0.6%, if longer opening hours gave them higher sales for the same amount of non-staff costs. In a competitive market, most of the benefits from a cost reduction of this kind would be passed on to consumers. Consumers would also gain from a greater ability to coordinate their trips (passing an open store while making another journey) and shop at less congested

times, but might lose out if convenience stores lost sales and were forced to close. Indepen (2006) valued these effects at around £1.5 billion a year.

We might see similar effects as the 24/7 society becomes more intense. Consumers can spread their shopping over more hours, and those shops that gain sales will see a reduction in unit costs. If the increase in sales per shop means that fewer new shops are opened, then there will be a saving in the total cost of shops, and the money saved can be spent on other things. If the increase in the shops that have extended their hours comes at the expense of others, then their unit costs will rise, reducing the total savings.

Online retailers' lower direct costs mean that the ratio between retail and wholesale prices will fall as the proportion of online sales increases. This implies that a given amount of consumer spending will buy a larger volume of products. To the extent that the UK is a net importer of consumer goods (as it is for all manufactured goods), this might worsen the balance of trade. However, changes in the balance of trade would have an impact on the exchange rate, which would itself feed back to exports and imports, and thus have a long-run tendency to be self-correcting. In fact, many of the changes from the 24/7 society will be self-correcting at a macroeconomic level. People do not gain more money to spend, simply because they can spread that spending over a longer proportion of the day. There will be individual effects, but the macroeconomic effects will tend to be muted by this basic fact.

4 Future Directions

4.1 Design

The non-stop society forces consumers to adopt lifestyles which are unsustainable (Reisch, 2001 in Shove, 2003). Individual behaviours are deeply guided by what others around us say and do. 'We do so because that's what everyone else does' (Sustainable Consumption Roundtable, 2006). The Internet is not expected to become the default shopping medium in the UK, the social aspects of shopping are simply too powerful. Nevertheless, its impact continues to grow. Internet sales rose by 45% in the UK during 2007, while retail sales grew by 4.5% over the same period (IMRG, 2008).

It is predicted that by 2020, 25% of UK population (over 13 million people) will be operating in the 24/7 culture. The increase is due to an increase in the disposable income of those in the higher earning brackets (Future Foundation, 2004). A total of 35% of households earning more than £46,000 and 20% of households earning £10,430 or less will take part in out-of-hours activities (Hicks, 2006). By 2020, 46% of the population will be over 45 years of age, and 39% of people will be aged between 25 and 45 years (Hicks, 2006).

Although behavioural patterns appear to be resistant to change, there is considerable evidence of radical technological and behavioural change in the uptake of products such as mobile phones, plasma TVs, power showers, standby modes in electronic appliances and air conditioning in cars (Jackson, 2005:105). This highlights the potential for designers to intervene more creatively to unlock 'bad habits' and to establish new opportunities for sustainable living. At the same time, increasing European directives (such as EuE) are focusing on the reduction of energy use in products and setting minimum energy performance standards. There is potential to lead to large reductions in household energy requirements as designers begin to consider these issues.

4.2 Energy Management

Among the new opportunities afforded by information technology is the ability to monitor and control the operation, and hence the energy performance of systems, buildings in particular. Termed 'building management systems' (BMS), or 'energy management systems' (EMS), they allow the status of the building and its energy-consuming systems (the building services systems) can be observed via a range of sensors, and appropriate action to be taken to change their operation. Control is frequently effected via control algorithms. They vary in complexity from digital versions of simple on/off, PID (proportional – integral – derivative), or optimum start/stop control, to advanced model-based control formats such as adaptive or predictive methodologies (see, for example, Liao *et al*., 2005). To date, such condition monitoring and control systems are usually restricted to commercial buildings, and there remains scope for their introduction into the domestic sector. More intelligent control of buildings and their systems might save in the region of 20% of energy consumption (Murakami *et al*, 2007). It is likely that the future will see an increase in the use of these technologies, with adoption of more advanced model-based strategies (EMS are capable of

implementing such digital control algorithms). Systems could take automatic account of occupants' needs 'learned' from their behaviour or detected by sensors (see, for example, Fisk and De Almeida, 1998; Liang and Du, 2007).This is a key area where the technology that has helped create the 24/7 'on-demand' society can also be used to manage and reduce its energy consumption.

The concept of providing the user with more information about their energy usage, to allow them the opportunity to change their behaviour, is also gaining ground. This is termed 'smart metering' (Bertoldi and Huld, 2006; Houseman, 2005; Kinver, 2006). An example of how design has begun to tackle this can be seen with the Flower Lamp from Sweden (see Figure 2). It is not just the light of the lamp but its form that reflects energy used. The lamp 'blooms' – changing its shape and thus lit expression – when energy consumption in a household has been low for some time. In order to make the lamp more beautiful, a change in behaviour is needed.

Figure 2. Flower Lamp (Interactive Institute, 2005)

4.3 Technology

In general, buildings are responsible for over 40% of the UK's carbon emissions, with transport giving rise to about 35% (Energy White Paper, 2003). It is estimated that energy efficiency measures have the potential to reduce primary energy consumption in Europe by over 20%, with the largest cost-effective savings potential being in households (27% savings)

and commercial buildings (30% savings) (European Commission, 2006 and 2007). Furthermore, there are commitments for a 20% reduction in energy consumption in Europe by 2020 (European Commission, 2004), as well as enhancement to the UK's targets for carbon reduction (UK Budget, 2008).

In line with these aims, the future is certain to see the increasing adoption of energy-saving measures, together with the likely integration of a mix of new and renewable energy technologies for space heating, water heating and power generation, as a means for the UK to make significant progress towards achieving its targets for carbon reduction. Technologies brought into use for the first time, or developed beyond their present scope, could include heat pumps, combined heat and power, photovoltaic and solar thermal collection and fuel cells. A review of low-carbon technologies for the built environment is given by the BRE Trust in partnership with the NHBC Foundation (Fisher *et al*, 2008).

Alongside the deployment of the new technologies, it will be essential to provide the necessary infrastructure to support their use. This will involve their manufacture, installation and maintenance, education and awareness and their eventual recycling. Interactions with users and wider society will need to be fully explored and accommodated. The role of hydrogen as the fuel of a future low-carbon economy is reviewed by McDowell and Eames (2006), including the factors that affect its rate of emergence.

Information technology offers an important means to reduce carbon emissions by complementing these technologies and by providing data to interface with user behaviour as outlined in the previous section. This may take the form of remote system monitoring and control by energy utilities, perhaps linked to localised energy storage that helps the management of demand, and assists in balancing the main grid infrastructure. Such storage techniques will also interface with the daily living patterns of the users. There will probably be increasing use of localised grids for power distribution as distributed generation increases. While information technology may well have helped to bring about the 'on-demand' culture, it can also be used to help curb and control energy demand.

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PUBLICATION B
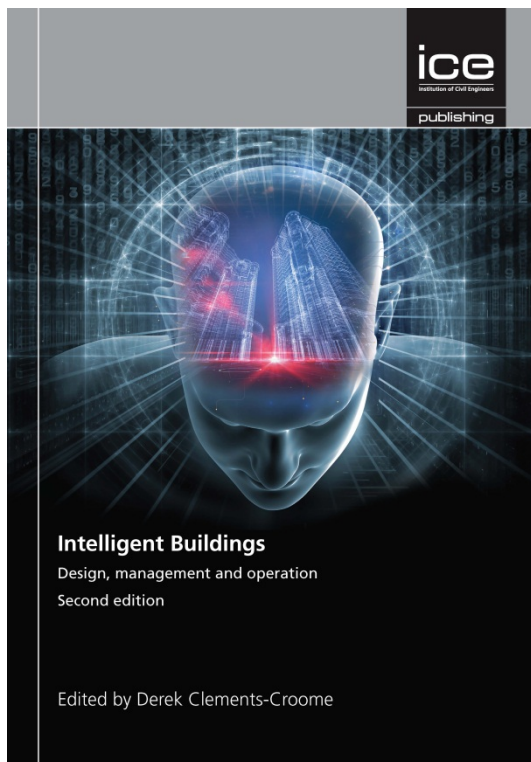
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The full chapter is presented in Intelligent Buildings: Design, management and Operation (2nd Ed). D. Clements-Croome. (Ed). London: ICE Publishing and is available through the ICE Virtual Library at http://www.icevirtuallibrary.com/content/book/102869

Abstract

Intelligent homes have been a vision for decades, with the 'Home of the Future' promising an automated, sophisticated place to live, packed with technology that responds to our every need. With a new focus on energy saving, intelligent homes are again being heralded as the way to a low carbon future. However, history demonstrates that people may not find the proposed technology simple to use, with issues of control, compatibility, trust and accessibility making this a problematic approach.

This chapter discusses the potential for intelligent energy saving in the home and explores the human factors that create pitfalls to the successful roll out of smart energy saving devices. The importance of understanding the user needs as a critical success factor and the role of user centred design in the development of intelligent products, services and systems is outlined. Whilst focused on the domestic sector, there are learnings relevant to all buildings where there are users.

Keywords

PUBLICATION C

Vadodaria, K., Loveday, D.L., Haines, V.J.A, Mitchell, V.A., Mallaband, B and Bayer, S. (2010). UK Solid-Wall Dwellings - Thermal Comfort, Energy Efficiency Refurbishment and the User Perspective - Some preliminary analysis from the CALEBRE Project. Adapting to Change: New Thinking on Comfort. Cumberland Lodge, Windsor, UK, 9-11 April 2010. London: Network for Comfort and Energy Use in Buildings, 1-16.

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Abstract

The paper discusses the state of solid wall housing in the UK, and the technical and socio-economical challenges that need to be addressed whilst refurbishing this stock. The challenges of improving the thermal performance of the envelope and of reducing space heating-related carbon emissions in solid wall housing are discussed together with issues related to thermal comfort, the 'take-back' process and user-appeal. Preliminary results of the Householder Survey of Project CALEBRE are presented, including the sample selection and survey processes. It is concluded that, irrespective of cost factors, the perceived benefits and aspirational appeal of carbon-reducing technologies need to outweigh the cost associated with disruption from the perspective of the householder. Achieving this places demanding requirements not only on technologists and designers but also upon those responsible for marketing essential energy saving solutions.

1 Introduction

1.1 Background

An overwhelming body of scientific evidence now clearly indicates that climate change is a serious and urgent issue. The earth's climate is rapidly changing, mainly as a result of increases in greenhouse gases caused by human activities. (Stern review report, 2006). The Stern review report states that if no action is taken to reduce emissions, the concentration of greenhouse gases in the atmosphere could reach double its pre-industrial level as early as 2035, resulting in a global average temperature rise of over 2°C and a 50% chance that the temperature rise would exceed 5°C in the long term. By 2100, the average summer temperature for the UK is expected to rise by between 1 and 6°C, depending on region and emissions scenario. Recognising the need for urgent action, the UK Government in November 2008 introduced the world's first long-term legally binding framework to reduce greenhouse gas emissions (the Climate Change Act 2008). According to this ambitious and legally binding contract, the UK will by 2050 reduce its greenhouse gas emissions to at least 80 per cent below 1990 levels.
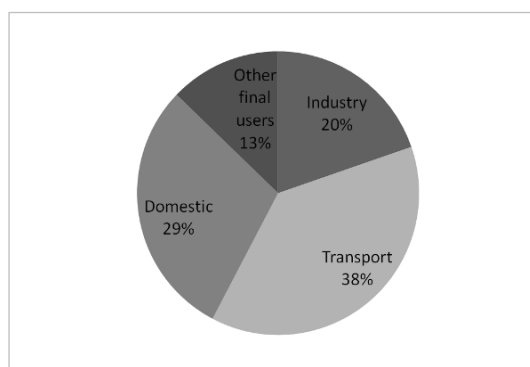
1.2 UK Energy Statistics

In the UK, carbon dioxide (CO2) emissions account for nearly 85 per cent of total UK greenhouse gas emissions. As shown in Fig. 1, net emissions of carbon dioxide in 2008 were provisionally estimated to be 531.8 million tonnes, 11% lower than 1990 levels (DECC, 2008).
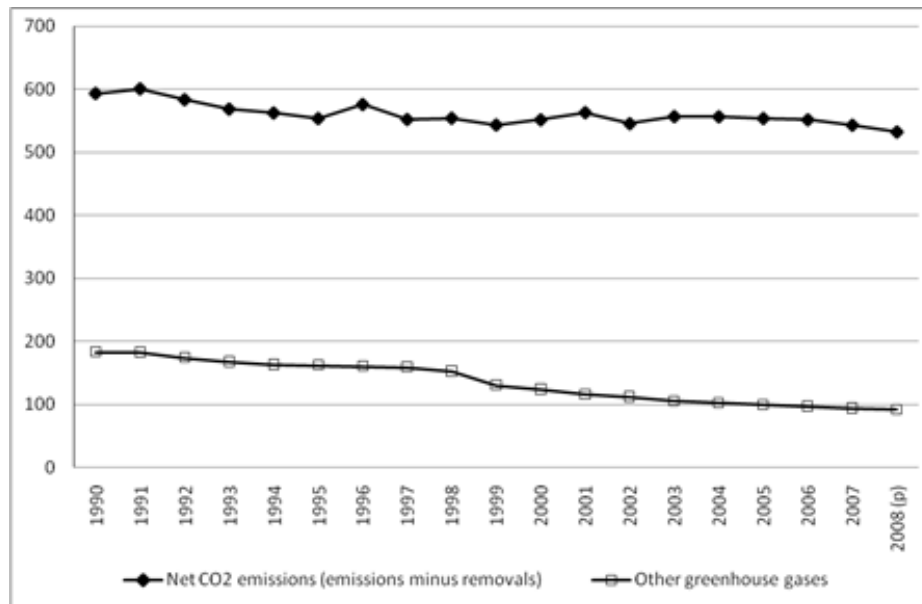

**Figure 1: Trajectory of UK carbon dioxide emissions
(drawn from DECC Energy Statistics data)**

A significant amount of these emissions (up to nearly 70%) are the result of energy used by buildings and industries as a whole with up to 30% of emissions from domestic buildings alone, as shown in Fig. 2.

Figure 2: Sector wise end use UK energy breakdown for 2008 (drawn from DECC Energy Statistics data)
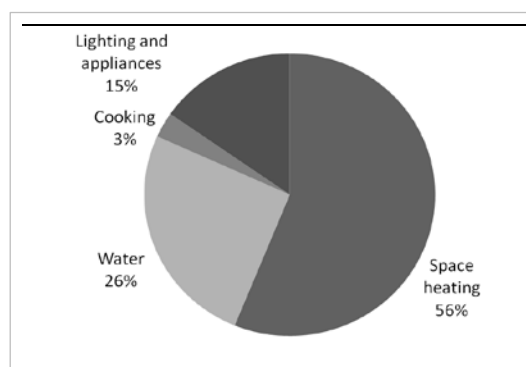
Figure 3: Domestic energy consumption by end use, 2007 (drawn from DECC Energy Statistics data)

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Recognising this fact, the UK Government has initiated a process of carbon reduction in buildings through amendments to Building Regulations The proposed target dates for zero carbon domestic buildings is 2016 and for non-domestic buildings is 2016-2019. However, while policies, regulations and technologies are being put in place to deliver new zero carbon buildings, it is the existing stock of domestic buildings that poses the greater threat (and opportunity) for achieving the ambitious 2050 targets. This is due to the fact that up to 75% of the stock that will exist in 2050 is already constructed and has been built prior to 2005 with consequent poorer fabric performance and low energy efficiency standards (Boardman *et al*, 2005). As shown in Fig. 3, emissions arising from this stock are primarily due to energy used in space heating (56%) and water heating (26%). Hence any attempt to reduce carbon emissions from the existing domestic stock needs to begin with improving the thermal performance of the existing stock, followed by installing energy efficient heating systems and other technologies, as required.

1.3 Solid wall housing- the extent of the problem

The existing stock currently amounts to a total of 26 million dwellings, the majority of it being cavity wall construction. Improvements to these dwellings are well under way through cavity wall insulation under initiatives like 'Warm Front' in England (EAGA, 2009). However, within the context of improving energy efficiency of existing stock, one sector has proved to be particularly difficult and problematic. Known as 'Hard to Treat' and 'Hard to Heat', these homes are defined by the Energy Saving Trust (BRE 2008), as 'homes that, for a variety of reasons, cannot accommodate 'staple' energy efficiency measures offered under schemes such as Warm Front in England'. These homes essentially include those that are off the gas network, solid wall properties, homes without loft space, homes in states of disrepair, high rise blocks and other homes where it is not possible to install staple energy efficiency measures due to technical and practical reasons. Staple energy efficiency measures include wall, loft and floor insulation, double glazing, draught proofing and efficient central heating systems.

According to the English House Conditions Survey 2006, Hard to Treat (HTT) homes currently comprise of 43% of the total stock, amounting to 9.2 million homes. Of these, solid wall dwellings alone constitute 6.6 million homes (72% of the HTT stock and 31% of total

stock). These solid wall dwellings were primarily built during the late 18th and 19th centuries and consist of a 230mm (9 inches) thick or greater solid wall construction, either in stone or brick.

The lack of cavity wall construction and hence the inability to conduct standard insulation type retrofits has led to inadequate thermal comfort and high energy consumption in solid wall dwellings. It was observed from the English House Condition Survey 2006 data that up to 80% of solid wall dwellings have a SAP rating less than the mean SAP rating of 48.3 SAP points for all dwellings as indicated in Fig. 4. SAP is the Government's Standard Assessment Procedure for Energy Rating of Dwellings. It is used as a national methodology for calculation of energy performance of existing buildings and to demonstrate compliance with building regulations for new dwellings (BRE, 2005). Furthermore, as shown in Fig. 5, 60% of solid wall dwellings have failed the decent homes standards due to inadequate thermal comfort, excess cold and high levels of condensation and mould. According to the Decent Homes Standards (DCLG, 2006), a decent home is defined as a dwelling that meets the following criteria:

a)   Meets the current statutory minimum standard for housing

b)   Is in a reasonable state of repair

c)   Has reasonably modern facilities and services

d)   Provides a reasonable degree of thermal comfort.

It was as a result of damp problems and higher costs, that the solid wall construction was replaced with cavity wall construction during the 1920s and 1930s housing boom (Beaumont, 2007).
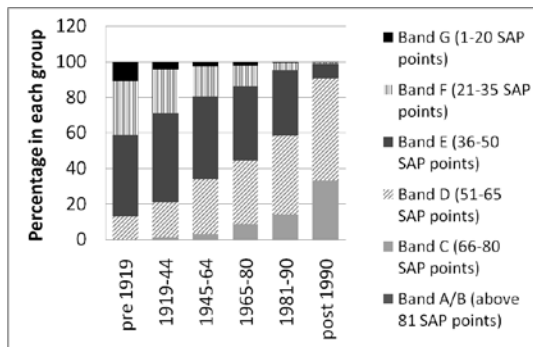
Figure 4. SAP Rating of English housing stock
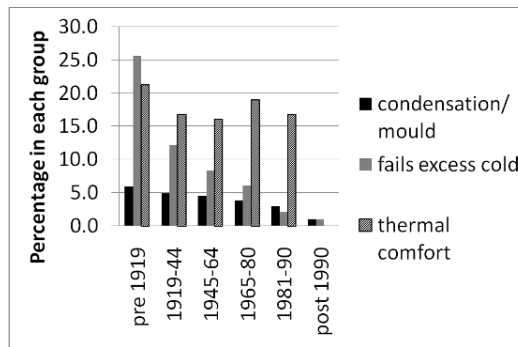
Figure 5. Percentage of solid wall housing failing Decent Homes standards

2 Challenges and Opportunities

Recent research (Johnston, 2005; Natarajan, 2007) has suggested that it is not possible to achieve the UK's 2050 carbon reduction target through a single solution or intervention, rather a set of measures is required. This will require a mix of interventions that will include:

- New measures to improve the thermal performance of the building envelope
- Improving the energy efficiency of heating systems and appliances
- Changes in personal attitudes towards energy consumption, lifestyles and thermal comfort- redefining the meaning of comfort
- Decarbonising the electric grid and use of renewables

2.1   Improving thermal performance of envelope and heating systems

Space heating in solid wall housing dominates the overall energy consumption as a result of poor performance of the building envelope. Hence, the biggest challenge in this stock is how to improve the thermal performance of its envelope and reduce heat losses. Due to the lack of cavity, solid wall dwellings will either require internal insulation or external insulation. Application of internal insulation reduces the net usable volume of room space and its installation typically causes disruption to the occupants of the dwelling, thus raising serious questions of appeal and acceptability to householders. Furthermore, with the application of internal insulation, the dwelling loses the moisture and heat storage benefits from the thermal mass provided by the solid wall. This combined with other improvements in the form of reducing air leakages may negatively affect occupant's health and comfort and

increase cooling loads. Studies employing future climate change forecasts (Hacker, 2008) have shown that heavyweight buildings tend to perform better in a future over heating scenario, where higher summer temperatures are expected in 2050 in the UK.

Applying external wall insulation to solid wall properties is an alternative to internal wall insulation and offers the advantages of avoiding disruption to the indoor living environment during application, in leaving internal useable floor area intact and more importantly not affecting the thermal mass storage capacity of the solid wall. However, its disadvantage is that it can be a less favourable option for the planning authorities and the heritage bodies in the cases of listed properties. Since the majority of solid wall properties were built before 1919, it is very likely that the majority of them would either have a listed status or come within a conservation area, thus making it very difficult to obtain listed building consent to carry out external insulation work.

Retrofit of current glazing systems and replacing single and double glazing with high performance vacuum glazing is a potential future solution that can achieve significant improvements to the thermal performance of solid wall dwellings and offer the potential to increase window to wall area ratios. According to the ECHS 2006 data, currently 28.4% of pre1919 stock has no double glazing. However, two issues are of primary concern here. Firstly, similar to external insulation, if a home is listed, replacing the glazing will be subject to obtaining listed building consent, decided often on a case-by-case basis by the planning officer and local authority conservation officer (English Heritage, 2008). The second issue related to replacement of double glazing is user appeal in terms of affordability. Pay back times for a replacement double glazing with low-e coating can be anywhere from 50 years (Menzies, 2005) to up to 97 years (DCLG, 2006) as shown in Fig. 6, making the option unattractive to householders, though benefits such as enhanced thermal comfort and reduced window condensation frequently prevail.
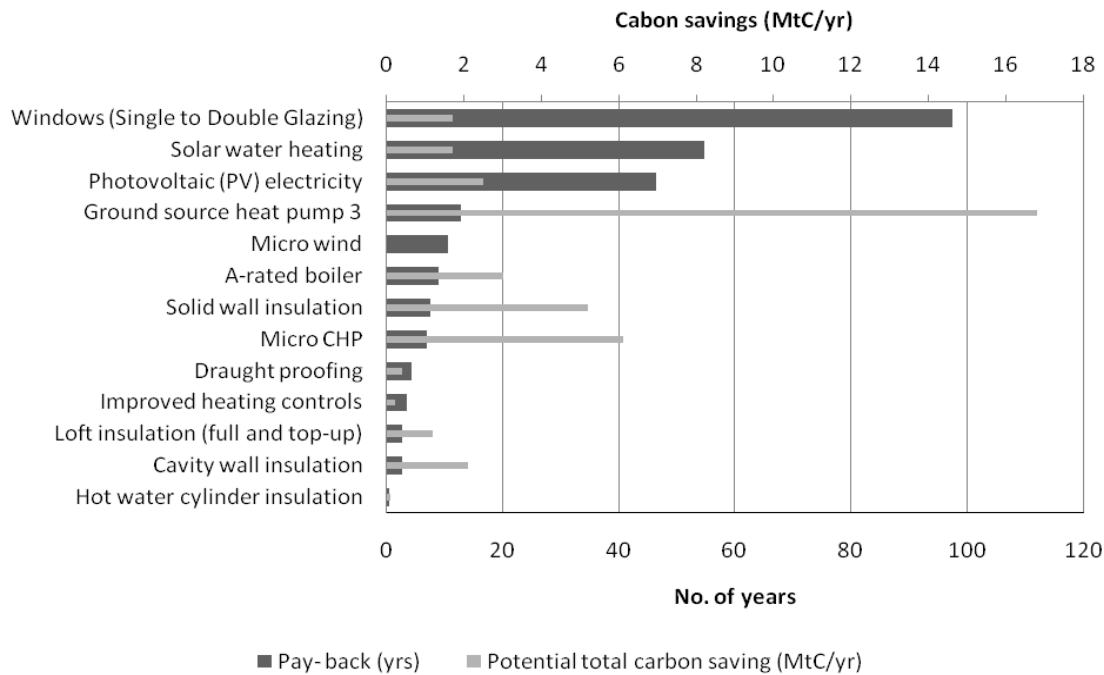
Figure 6: Comparison of pay-back times and carbon saving potential of retrofit technologies. (Drawn from data published in Review of Sustainability of Existing Buildings, DCLG, 2006)

Overcoming these challenges to improve the fabric performance of solid wall properties will itself be insufficient to deliver the required reductions in UK carbon emissions. The supply and management of heat and power is as important an issue as the reduction in heat demand. Gas condensing boilers will need to be replaced with, for example, heat pumps and other microgeneration technologies that offer higher efficiency and carbon reduction potential. However, the extent of uptake of these technologies will again depend on the degree of user appeal that they offer in terms of affordability and payback times, ease of installation, operation and maintenance, size and aesthetics and technical performance. For example, the cost and feasibility of ground source heat pumps vary depending on the geological and environmental conditions of the site and air source heat pumps, an emerging technology and alternative to ground source heat pumps are three times more expensive than an A rated boiler.

2.2 Thermal Comfort, take-back process and user-appeal

Another significant challenge that needs to be addressed is people's attitudes toward energy consumption, together with the 'take-back' process where people choose to

improve their thermal comfort through energy efficiency measures introduced as part of retrofit process. Studies of American houses (Steemers, 2009) have shown that while the most important parameter that affects energy use is climate, the second most important factor that affects energy use is occupant behaviour, specifically in terms of the choices made about heating and cooling systems and their control. This aligns with the Warm Front Studies in the UK (Hong *et al*, 2006), where it was observed that although Warm Front measures did improve SAP ratings and improve indoor temperatures and thermal comfort, there was an increase in overall fuel consumption as a result of the take-back process. This can be explained by the answers received in the qualitative interviews. Respondents said, 'Now we can use the whole house instead of hugging around a living room fire'. Further analysis by Hong *et al* (2009) revealed that Warm Front measures led to an increase in the whole house neutral temperature from 18.9°C to 19.1°C. This resulted in a reduced clothing level, indicating a take-back associated with behavioural changes. Predicted Mean Vote (PMV) analysis predicted a higher neutral temperature of 20.4°C compared to 18.9°C which was found to be ideal among the average Warm Front households. Hong *et al* concludes that while a large portion of the take-back from insulation can be explained as the result of improved thermal performance of the building fabric the take-back associated with central heating supports occupancy behaviour as the primary cause. Previous studies by Hong *et al* (2006) also revealed reductions in space heating fuel consumption (due to cavity wall and loft insulation) of 10% in centrally heated properties and 17% in non-centrally heated properties, as compared with theoretically expected reductions of 45-49%. This was considered partly due to inability to achieve 100% insulation and party due to the take-back process initiated by the improved thermal comfort.

Thus, the challenges in the refurbishment of existing houses to reduce carbon emissions are varied and complex. The refurbishment approach will also have to address not only the technological and socio-economical challenges of retrofit technologies but will have to ensure that acceptable thermal comfort is achieved without the loss of energy savings through the take-back process. These challenges require an in-depth understanding of the relationship between domestic buildings, retrofit technologies and the user needs in terms of acceptability, appeal and thermal comfort so as to deliver low/zero carbon buildings that remain acceptable for comfortable occupation. With this in mind, Project CALEBRE

(Consumer Appealing Low Energy technologies for Building REtrofitting), a four year EPSRC / E.ON - funded research project, is investigating user-appealing technology packages that can achieve this for solid-wall housing.

3 PROJECT CALEBRE

The overall aim of Project CALEBRE is to establish a validated, comprehensive mechanism for reducing UK domestic carbon emissions within solid walled housing that is acceptable and appealing to users. The project takes the approach of identifying, from a user perspective, the barriers and key challenges to the deployment of retrofit carbon-reduction technologies, and then by using the knowledge gained through householder engagement and surveys to appropriately modify selected technologies for field-trialling and user evaluation including thermal comfort evaluation.

The selected technologies include electric and gas-fired heat pumps, home ventilation heat recovery, energy-efficient vacuum glazing and innovative advanced surface treatments to control temperature and moisture via nano-technology. The technologies will be uniquely informed by the reality of the user perspective, addressing such questions as the degree of disturbance that householders are prepared to tolerate during a refurbishment programme. Having been developed and modified keeping in mind the user perspective, these technologies will be trialled using the newly-constructed occupied E.ON test house, specially built to 1930s standards, and located on the campus of Nottingham University. These technologies will be evaluated not only in terms of their performance and efficiencies but also in terms of their impact on the thermal comfort of the occupants. The outcomes from the work will include a software tool for use by relevant stakeholders, and could form the basis for a 'one-stop-shop' for householders to identify and purchase their carbon reduction package.

At the time of writing this paper, the householder engagement process has begun, based on a 'representative' sample of solid wall dwellings and a selection of case studies. Techniques include recruiting of householders, preliminary site visits, interviews and data collection.

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4 Householder Engagement

4.1 Sample Selection

The English House Condition Survey (EHCS) is the most comprehensive national survey of housing stock in England, commissioned by the UK Government's Department of Communities and Local Government. Conducted since 1971, this survey covers all tenures and involves a physical inspection of properties by professional surveyors. The information obtained through the survey provides an accurate picture of the dwelling stock profile in terms of its age, construction, type, size, tenure, household, occupancy, energy efficiency, type of fuel used, decent homes standards, state of disrepair and liveability.

For our study, the statistical analysis software SPSS was used to analyse the EHCS 2006 data to derive a representative sample of a 'typical' solid wall dwelling in England. The following was observed:

- Dwelling Type: 70% of the total solid wall housing stock consists of end terrace, mid terrace, semi detached and detached property types (see Fig. 7).
- Dwelling Size: 85% of solid wall properties have an area of more than 50sqm, the remaining 15% (being less than 50sqm) comprising 1-2 bedroom properties) (see Fig. 8)
- Regional Locations (Government office regions): 30% of the total solid wall housing stock is in London, while less than 3% are in the north east, the rest being located evenly in other regions. (see Fig. 9)
- Regional Location (urban /rural): 75% of the total solid wall housing stock is located in urban centres (not city centres) and suburban residential regions. (See Fig. 10)
- Type of Tenure: 80% of the total solid wall housing stock is owner occupied and privately rented occupied. (see Fig.11)
- Type of Fuel Used: Majority of all solid wall properties (up to 85%) used gas for heating. (see Fig. 12)
- Household Composition: Solid wall properties have an even mix of household composition which includes couples less than 60 years of age with and without

dependent children, couples above the age of 60 years with no dependent children, multi person household and lone parents. (see Fig. 13)

- Household Size: 90% of solid wall properties have a household size in the range of 1 to 4 with less than 10% having an occupancy greater than 4 (see Fig.14).

- SAP rating: 50% of solid wall properties have a SAP rating in the range of 30 to 50, the mean rating of all property types being 49.8 SAP points (see Fig.15).

- Failing Decent Homes Standard: Analysis of the ECHS (2006) data indicates that while 60% of solid wall housing stock failed the decent homes standard on insulation measures alone, 30% of the stock failed on heating measures and 10% of the stock failed on insulation and heating measures (see Fig. 16).
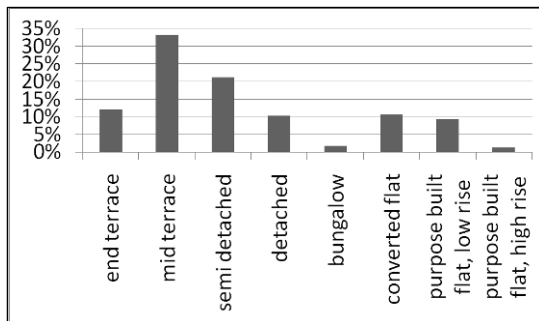
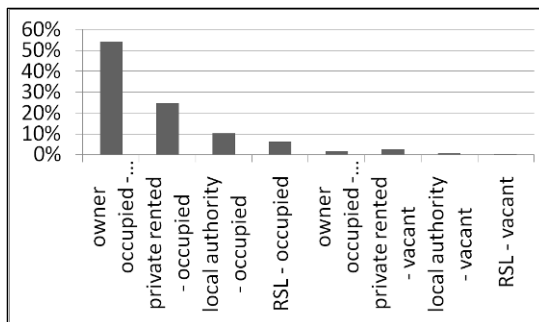**Figure 7: Dwelling types in solid wall housing**
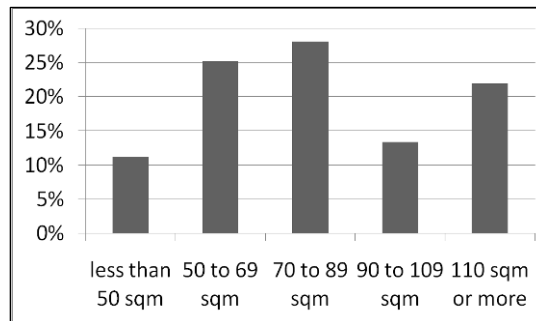
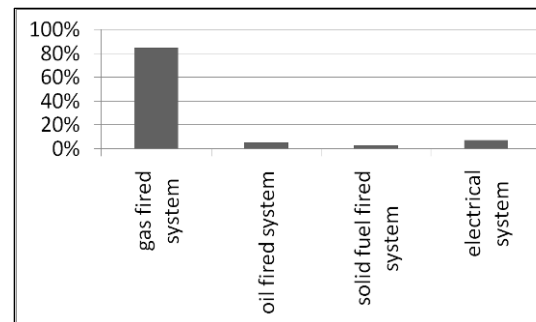**Figure 8: Dwelling sizes in solid wall housing**
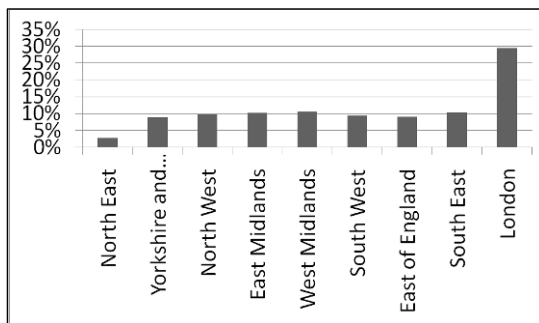
Figure 9: Distribution of solid wall housing in Government Office regions
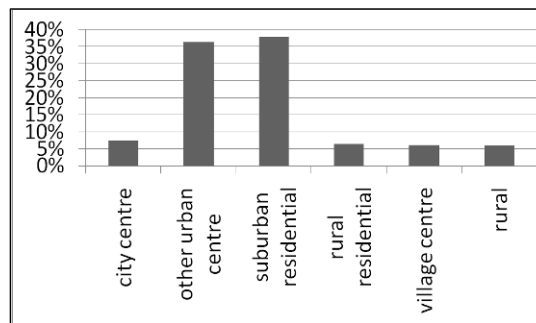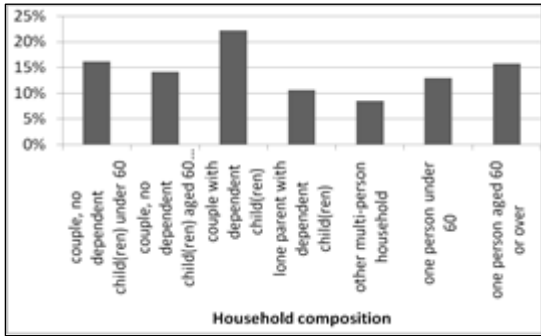

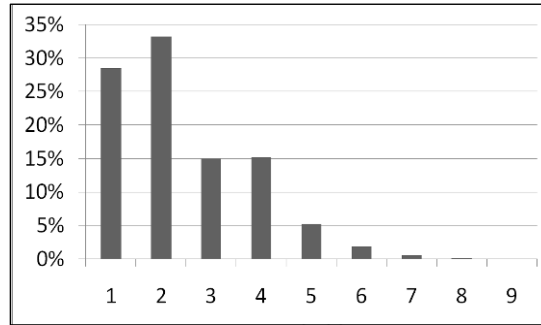**Figure 10: Distribution of solid wall housing (urban-rural)**

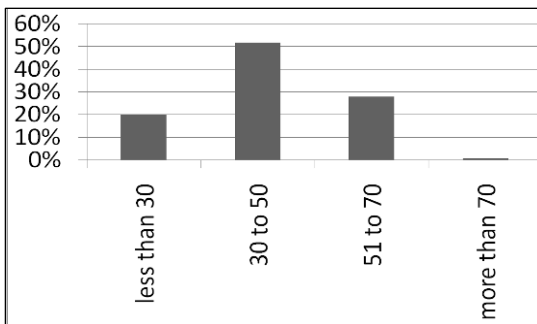**Figure 11: Types of tenure in solid wall housing**

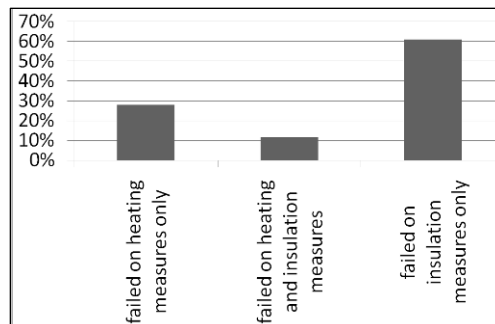**Figure 12: Type of fuel used in solid wall housing**

Figure 13: Household composition in solid wall housing

Figure 14: Size of household in solid wall housing

Figure 15: SAP rating of solid wall housing

Figure 16: Solid wall housing failing Decent Homes Standard

From the above data, it was concluded that a 'representative' sample of solid wall dwellings in England would be made up from houses that were end terrace, mid terrace, semi-detached and detached properties, occupied by owners and private tenants, with household size in the range of 1 to 4, having an even mix of household composition (ranging from singles, couples with and without children and elderly singles and couples) and having mains gas heating. Selecting a location in Leicestershire, East Midlands (around the town of Loughborough, within reasonable distance of the University) would offer similar representation to many Government Office Region (with the exception of London and the North East).

4.2   Householder Survey

The first stage of the research is focusing on engagement with householders, through in depth discussions with householders in their homes. A mixed methodology approach is being used, collecting qualitative and quantitative data focusing on the wider perspective of home improvement. With reference to the selection criteria of section 4.1, twenty

households were identified, and formed the sample for this stage of data collection. The sample encompassed a range of house and household types, including young couples, families at different life stages (e.g. new baby, empty nesters) and older people. Snowball sampling was used to recruit participants, focusing on urban and suburban properties in the East Midlands in the UK.

A multi stage approach is being taken:

- Visit One – To understand people's motivations and experiences with home improvements, including issues of disruption, cost and service provision.
- Between Visits One and Two – Comfort investigation – investigating thermal and additional subjective comfort factors and collecting temperature and relative humidity data.
- Visit Two – To explore with householders the consumer appeal and practical acceptability of specific CALEBRE technologies. This includes gathering data on architectural features of the home that might impinge on retrofitting, or space limitations to prevent installation of interventions.
- Visit Three – To conduct an Energy Performance Certificate (EPC) assessment with supplementary survey questions to provide detailed data on the thermal characteristics and performance of each house.

This paper presents initial findings from Visit One only. The methodology for the first visit drew on the principles of participative design (Ehn and Sjögren, 1991) in order to elicit rich data from householders and to establish rapport. Researchers were sensitive to the privacy of the home environment and so this first meeting was conducted in a place in the home where householders would be accustomed to greeting guests – typically round a dining room table. Wherever possible, interviews were conducted with all adult members of the household, as the decision to undertake home improvements is often a collective one. In some cases, older children also participated in the discussions, providing a wider household perspective.

Householders were asked about their past behaviours and experiences of home improvements and renovations in order for the researchers to ground understanding of how people are likely to respond to future retrofit interventions. Prompted recollection techniques (e.g. Mitchell *et al* 2004) were used to help householders recollect the home improvements made since moving in. This focused around the development of a time line, with key information being built up using magnetic cards to denote key life stages, home improvements and dates. Additional detail was annotated onto the time line as the discussion progressed; see Figure 17 for an overview of a complete time line from one household.
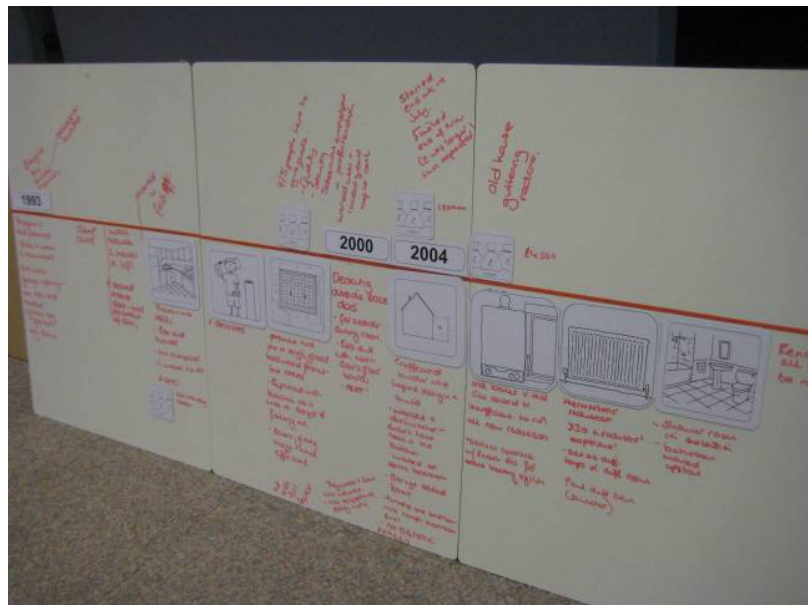
Figure 17: Example time line

Comfort and future aspirations relating to home improvements were also explored.

During Visit One, householders were not explicitly asked about energy efficiency measures in order to provide a broader perspective on the motivations for home improvements. Questions asked during Visit One included the following:

- What major changes have you made to the house and why? Have you decorated as well? What was the cost and level of disruption for changes? What were the barriers / triggers?

- Within your home, what does comfort mean to you? How do you create comfort in your home? What areas of your house are comfortable or uncomfortable and why?

Understanding patterns of home improvement to identify the best opportunities for retrofitting energy efficient measures during the life cycle of a property is an important issue for CALEBRE. Exploration of issues relating to the home improvements process will help determine whether retrofit measures are most acceptably installed as a one-off, or gradually over a number of months or even years.

Between Visit One and Visit Two, householders will record examples of times when they were uncomfortable (too hot or cold, too humid or dry, too draughty or stuffy) and what they did to alleviate this. A record of temperature and humidity levels in two main rooms in the home will also be made, in an attempt to see if there are any link between the subjective responses of the householders and the thermal environment. By analysing the subjective ratings alongside the temperature and humidity in the home at the time, patterns of preference may be identified.

Once this context is established, the second visit will focus on specific energy efficiency measures (interventions) and probe more directly the householders' attitudes to energy conservation.

5 Data Analysis and Discussion

Preliminary findings from Visit One are presented in this paper. Data from the visits were transcribed and thematic analysis, a flexible method for identifying, analysing and reporting patterns within qualitative data (e.g. Braun and Clarke, 2006), was used to identify key issues under a range of pre-determined themes.

5.1 Reasons for living in the property

In addition to issues of cost and location, the householders had particular reasons for purchasing older properties. Many cited the character and architectural features of the

house as being appealing, features which they felt were lacking in newer properties. The quality of workmanship associated with older properties was valued:

"This house feels like it's been built with pride."

Also, householders often mentioned that they relished the challenge of undertaking the renovation of an older house.

5.2   Patterns of Home Improvement

All householders had undertaken some major home improvements since moving in. These included loft conversions, new kitchens and bathrooms, structural alterations to the house, improvements to the heating system, new windows and doors. It was noticeable that many householders undertook significant home improvements in the first few months after purchase, sometimes before they moved in. This allowed for major renovation to take place during an already disrupted period. This period of intensive renovation typically lasted between two and six months. In some cases this was required to raise the living standard and thermal comfort of the property to an acceptable level, e.g. fitting a central heating system; in other cases the cost of major improvements was more easily assimilated into the overall cost of the move.

Once established in the home, householders continued to improve their properties or adapted their house to changing family circumstances, e.g. the birth of a child, growing teenagers or choosing to work at home. Redecoration was common, but did not always match the cycle of major home improvements and was fitted in whenever time and enthusiasm allowed. The majority of householders undertook significant renovation projects themselves, utilising existing or newly learned DIY (Do-It-Yourself) skills. This meant the cost of improvements was kept to a minimum, the householder could keep control of the job and in some cases, gain personal satisfaction from the achievement. However, there was evidence of householders picking and choosing the jobs they undertook, based on time and motivation, often influenced by particular stages in their lives. Trades people were used where a particular skill was needed or where the householder did not want to do the job themselves, but the early analysis of the data show a trend for these householders to favour a DIY approach, even if this lead to an improvement taking a much longer time to complete.

5.3 Levels of Disruption

Householders tolerated surprising levels of disruption, sometimes living without kitchens or bathrooms for weeks at a time. Jobs that could be fitted around patterns of daily living were not seen as disruptive, as household life could continue as normal. However, unexpected complications or delays caused considerable stress, and some householders commented that if they had known what was involved in advance, they would not have embarked on a particular project. This issue of understanding why disruption is acceptable in some cases and not in others needs to be further understood to inform future retrofitting programmes. It may be necessary to make the acquisition of carbon reducing technologies as appealing to householders as a new kitchen or bathroom, in order for the householder to put up with significant disruption. Such issues are being explored in Visit Two.

5.4 Barriers and Motivations to Home Improvement

Whilst householders were keen for renovations and improvements to be made to their home, a number of barriers have been uncovered from the initial analysis. There were examples of a considerable time lapse between identifying the need for and actually carrying out improvements. Delays could be attributed to:

- Cost – being able to afford to pay for materials or labour.
- Finding an appropriate tradesperson – finding someone the householders trust to do the job, obtaining a range of quotes and scheduling the work to be done.
- Weather – carrying out the work at the appropriate time of the year.
- Time – finding time to begin and complete the job, particularly when it was done by the householder.
- Life events – the arrival of a new baby or the breakup of a marriage, putting a strain on time and resources.

Householders were also motivated to make home improvements by a range of factors:

- Space – extending the house to make more space, or modifications to make better use of existing space.
- Repairs – to deteriorating or damaged features of the home such as windows or roofs.
- Discomfort – replacing windows or floors to minimise draughts.

- Efficiency – improving heating systems or insulation to reduce energy bills.
- Intrinsic factors – personal satisfaction, gaining a sense of achievement or relaxation, pride in restoration and a high standard of workmanship.

Although these results are from only preliminary analysis, as house visits are still on-going at the time of writing, an insight into the home improvement habits of householders in older, solid walled properties is emerging.

6 Assessing Thermal Comfort in Solid Wall Dwellings

Besides collecting qualitative and quantitative data focusing on the wider perspective of home improvement, Project CALEBRE is also attempting to assess the state of thermal comfort in Solid Wall Dwelling in the UK. Assessing people's comfort in their own homes is a challenging task as compared to lab-based thermal comfort study where there is greater control of environmental conditions and subjects. Hence Project CALEBRE is currently developing ways to successfully achieve this in these houses. Assessment of the thermal comfort in these solid wall dwelling will be done through a comparative analysis of the Actual Mean Votes (AMVs) and Predicted Mean Votes (PMVs). Project CALEBRE is currently in the process of formulating a standard thermal comfort questionnaire derived from ISO10551 standards. This questionnaire is aimed at being simple to understand and quick to complete and will be handed out to householders. Householder will be requested to complete this questionnaire after having seated in their sofa for at least 30minutes, for example after having watched their favourite television program in the evening, thereby ensuring a steady thermal state in the living room.

Temperature and humidity loggers will be placed in the same living room where the householders complete the questionnaire. As regards air velocity, assumptions will be made based on house visits. Unless a house is very draught, air velocity is usually less than 0.1m/sec in winter when windows are usually kept closed. Air velocity of 0.1m/sec is the minimum default value selected by ASHRAE Thermal Comfort Program (Version 1.0) used to calculate PMV values. Corresponding met values will be used assuming sedentary activity levels. To calculate clothing insulation level, a simplified clothing insulation list has been

developed from ISO7730 standards and this will be given out to householders to calculate and report a total for their clothing. Given the time scales of the study, it is not possible to measure mean radiant temperature in all houses. Hence mean radiant temperature will be measured in 20-30 houses and compared with air temperature values recorded during the same time. A conversion factor will be identified and applied to air temperature recorded in remaining house to derive a theoretical value for mean radiant temperature.

We anticipate that the comparison of AMVs and PMVs will lead us to a better understanding of the state of thermal comfort in solid wall dwelling in the UK. For example it will indicate levels of temperatures at which people feel comfortable and whether indoor temperatures do always need to be at least 21 degrees in living room and 18 degrees in bedrooms to ensure comfortable occupation.

7 Conclusion

The solid wall housing stock constitutes 31% of the total housing stock in the UK and offers a great opportunity to reduce UK domestic carbon emissions. A suite of retrofit solution and technologies will be required to reduce carbon emissions in this stock through a tripartite approach dealing with reduction of heat demand, supply of energy and management of energy. Technological and socio-economical challenges in the deployment of these solutions and technologies will have to be overcome. Human needs of adequate thermal comfort, user appeal and acceptability will have to be considered whist developing these solutions- thus requiring a bottom-up user centred approach towards a low carbon world. Thermal comfort will have to be understood from the householder's perspective and the impact of the take-back process will have to be considered while evaluating the carbon reduction potential of retrofit solutions.

By relating experiences of past home improvements, the barriers and motivations to future retrofitting of energy saving measures can be anticipated. Householders are clearly aware of energy saving measures, although their primary motivations for a home improvement were usually not to save energy. Improving living standards and reducing bills were more significant drivers. Irrespective of cost factors, the perceived benefits and aspirational

appeal of carbon reducing technologies need to outweigh the cost of disruption from the perspective of the householder. Achieving this, places demanding requirements not only on technologists and designers but also upon those responsible for marketing essential energy saving solutions.

This paper has presented preliminary results of the Householder Survey only. The ongoing work will collect additional data on householders' motivations for, and barriers against, retrofit energy saving technologies, as well as temperature and humidity recordings related to householders' responses to thermal comfort. CALEBRE is attempting to understand the state of thermal comfort in solid wall houses and get a look behind Britain's front doors!

Acknowledgment

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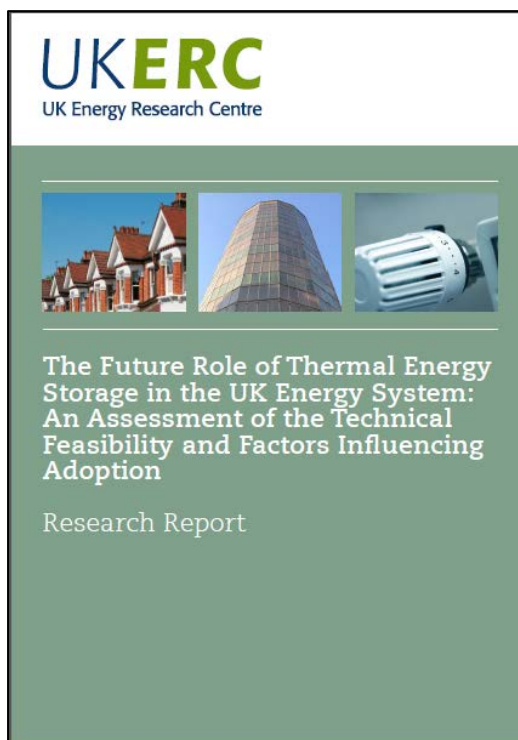
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Executive Summary of the full report

The aims of the work undertaken were:

- To characterise the main areas of heat use in the UK and the magnitude of the primary energy used

- To describe the main characteristics of the different technologies and approaches available for thermal energy storage and provide examples of their availability, deployment and demonstration

- To review current thermal energy storage system research to determine key characteristics, costs, maturity and additional research requirements

- To identify key application areas for thermal energy storage in the UK based on a national target for an 80% reduction in greenhouse gas emissions by 2050

- When combined with large scale deployment of electric air source heat pumps, to explore the potential for peak grid load balancing and the magnitude of thermal energy storage that could be achieved on a distributed basis.

Key findings of the full report

Just under half (45-47%) of total final energy consumption in the UK is currently used for heating purposes with approximately 80% derived from fossil fuels. Of the total national heat demand, space and water heating account for 63% and 14%, respectively. The domestic sector is responsible for 57% of total heat use with 77.5% being for space heating. Of the 18% of heat supplied for industrial processes, 6% is for high temperature process, 9% for low temperature process and 3% for drying and separation. Due to the large seasonal variation in space heating requirements, the annual heat load profile is far from constant, with the peak winter heat load being several times that of the average heat load.

At present, sensible heat storage is by far the most utilised and mature form of heat storage system, with most current thermal energy storage installations being based on this approach. Store volumes range in size from domestic hot water tanks and electric storage radiators designed to store heat for a few hours to systems with volumes up to 75,000 m^3 used for inter seasonal storage. Latent heat and thermochemical heat storage systems,

although potentially providing greater energy storage for a given volume, are still at lower technology readiness levels.

The four main types of large scale, low temperature, thermal energy stores that have been successfully developed are: tank thermal energy stores, pit thermal energy stores, borehole thermal energy stores and aquifer thermal energy stores.

Large inter-seasonal stores are only sized for a maximum of a few hundred buildings. Due to the annual operational cycle, the store cost must be low to provide payback on investment. There is a strong relationship between store size and cost, with small tank storage systems of $300m^3$ of water costing about £390/m^3, whilst for a pit store with a volume of 75,000m^3 of water equivalent, costs may reduce to around £25/m^3. The district heating system at Pimlico (one of the systems examined in this project) effectively uses a 2,500m^3 volume water store constructed in the 1950s to provide a short term balancing function for a CHP system supplying 3256 homes, 50 businesses and three schools.

Until such time as the existing building stock is radically transformed to be much more thermally efficient, or replaced with energy efficient new build, the greatest use of heat in the UK is likely to remain that for space heating. To achieve the significant planned reductions in greenhouse gas emissions, low emission heating approaches will be essential. Electric heat pumps operated with a decarbonised electricity supply and district heating can help address this problem. To assess the feasibility of these approaches two case studies have been undertaken, i) for domestic heating using data for a dwelling in Derby and ii) for the Pimlico district heating scheme in London.

In the first case study, daily winter heat requirements and daily peak heat requirements were determined for a large family house in Derby and scaled, based on the predicted performance if the house was compliant with the Building Regulations of 1980, 1990 and 2010. Thermal stores were then sized to meet the maximum space heat load for a three hour period to allow heat pump operation at periods of low electrical grid load. For a water-based sensible heat store, the storage volumes required were found to range from 2.6m^3 for the house constructed to 1980s Building Regulations, to 0.56m^3 for construction to 2010

Building Regulations. A "theoretical" phase change material (PCM) based store could reduce these volumes by two thirds. Given that PCM storage is likely to become a viable technology in the next few years, PCM-based thermal storage in conjunction with an electric air-source heat pump, offered as part of a Green Deal, was examined and found to be technically possible in a retrofit context. If operated in conjunction with an appropriate demand side management strategy, this type of system has the potential to support domestic energy demand reduction while at the same time minimising supply challenges for the electricity utilities.

In the second case study, an analysis was undertaken of the Pimlico District Heating Undertaking which includes a 2500m^3 thermal store built in the 1950s. The thermal energy store provides a balancing function to match variable supply and demand and also offers an emergency buffer to ensure seamless supply in the event of planned or unexpected maintenance. The thermal store at Pimlico District Heating Undertaking allows better control and plant efficiency; without the thermal store, the system would need to vary in operation to meet the changing demand, and so run inefficiently.

An analysis was undertaken of the potential additional national electrical generation and peak grid load resulting from the deployment of different numbers of air source heat pumps with different performance characteristics. In addition the potential storage in GWh of heat and electric equivalent that could be achieved with distributed thermal storage was calculated. For example, two million air source heat pumps with a winter COP of 2, each meeting a 12kW thermal load, would require an extra 12GW of electrical generation (compared to a current winter peak load of just under 60GW). If each dwelling equipped with a heat pump system had three hours of thermal storage, i.e. 36kWh to enable demand shifting, then the equivalent electrical storage would be 36GWh.

Provision of heat in the transition to a low carbon economy is a significant challenge. Heat networks currently supply less than 2% of the UK's space heating compared to approximately 16% in Germany. Heat networks allow large scale storage systems to be used that provide efficient storage and effective load shifting capability; expansion of heat networks in the UK is possible in areas of high heat demand although cost of installations is

high at present. If the electricity supply is decarbonised, combined heat and power will no longer be the lowest carbon option and large MW-scale heat pumps may prove preferential. The wide-scale adoption of air source heat pumps for space heating will require significant investments due to the seasonal variation and magnitude of peak winter loads.

Strengthening of the low voltage electrical network and significant additional generation capacity will be needed in addition to major building refurbishment to reduce heat loads. Distributed thermal energy storage can provide a significant load shifting capability on a diurnal basis. However, without the development of effective latent or thermochemical heat storage systems, the storage volumes required will be large and difficult to integrate into existing domestic dwellings.

Chapter 5. Case study 2: Exploring the non-technical barriers to UK deployment

5.1   Introduction

As outlined already within this report, thermal energy storage has the potential to store heat for later use over a period of hours, days, weeks or months. With a variety of approaches available, it offers the potential to supplement the energy supply system and is used in a wide number of applications in Europe and elsewhere and, as a means to optimise performance, is expected to become more widespread [34]. However there are a number of non-technical barriers to deployment in the UK and these are explored here, through use of a case study (Pimlico District Heating Undertaking, which includes a thermal energy store). There are a number of reviews of thermal energy storage systems, but few include details of the non-technical advantages and barriers to adoption. A review of social acceptance of a range of energy technologies [35] (although not including storage) recognises that this topic has had little attention to date.

5.2   The Approach Adopted

This case study was based on the limited published material about the Pimlico District Heating Undertaking (PDHU) and other relevant literature as well as a detailed interview with the key managers of the system, supported by a visit to the site. In addition to notes and photographs taken, the discussions were recorded and transcribed for later analysis. Other documents supplied by PDHU were studied to provide additional supporting material to the review. A detailed analysis of the thermal performance of the Pimlico District heating system falls outside the scope of this report but is included in an EngD thesis currently in preparation and available in summer 2014 [43].

5.3   Pimlico District Heating Undertaking

Pimlico District Heating Undertaking (PDHU) is a district heating system that is owned and operated by Westminster City Council's CityWest Homes and provides heating and hot water to 3256 homes, 50 commercial properties and 3 schools in the Pimlico district of London, UK. Built in the 1950s, it originally used waste heat from Battersea Power Station. Now, with three 8MWth boilers and two 2MWth combined heat and power (CHP) engines,

it generates electricity that is sold to the grid and provides heating and hot water to the properties served. The site is staffed by 2 full time engineers and 3 part time staff (manager, finance/contract manager, administrator). Additional contractors provide support for operational issues and minor repairs for the whole system and there is a call out system in place to provide out of hours service. The thermal energy store (see Figure 19), also referred to as the accumulator, is located above ground adjacent to the Energy Centre and Pump House, where the CHP engines are located and central operation takes place. The thermal store is a 41m tall tower, containing 2,500 tonnes water maintained at just below boiling point and contains approximately 18MWh of heat. The accumulator serves five purposes:

1. As an expansion tank to take up variations in water volume in the heating system

2. To act as a feed tank to make up losses in the system, although these can be minimal, e.g. 1.5 cubic meters over the whole system

3. To act as a heat store

4. To act as a seamless source of heat

5. To act as a cool store for the CHP engines.

Figure 19. The thermal store at Pimlico District Heating Undertaking

5.4   Social Impact

Thermal energy stores have the potential to provide positive social impact through the provision of heat. For those properties in fuel poverty (where the household cannot afford to keep adequately warm at reasonable cost), a district heating system, in conjunction with a thermal store, can provide a constant heat supply at a known cost. Within a district heating system where heat delivery is part of the social housing provision, it is possible to ensure that all homes are heated adequately and efficiently; this may need to be at a subsidised cost. The domestic properties at Pimlico make a payment for provision of heating and hot water at a rate based on the size of their property; the income of the household or length of daily occupancy is not considered. Comparison of price with conventional gas central heating is not easy – residents pay for heat, not fuel, and incur no maintenance costs of the system. A tenant in a one bedroom flat pays £479.77 per annum, those in a 5 bedroom flat pay £1,115.92 (2013 prices). Heating is provided to all properties from approximately 1 October to 1 June, and for up to 20 hours per day (5am to 1am in the coldest weeks, 6am to 11pm for the rest of the heating period), without metering. Commercial properties are metered and so pay for the exact amount of heat and hot water used. A boiler may be cheaper but it is likely that the home will be much colder as it would not be on for so many hours. The payment for heat, not fuel, also makes the district heating system more efficient for householders. The lack of an individual boiler within each property also maximises the living space.

Provision of heating for such an extended period of time ensures that vulnerable tenants who may need a warmer thermal environment to maintain health are well catered for. This increases the social impact, for example by reducing mould that may develop and so improving health. Provision of a thermally comfortable environment throughout a domestic property will enable the whole house to be used effectively, e.g. allowing comfortable space for children to do homework, people to bath in comfort etc. A thermal store can ensure there is always adequate warmth, providing a buffer during peak demand. The accumulator at Pimlico is used in this way, ensuring a constant service even during times of maintenance. There are occasional breaks in service, when there are more significant problems, such as major leaks, fire alarms etc. The length of this buffer depends on the level of charge of the accumulator, the external temperature, the season etc. In the summer, it may be possible to

supply the whole community all day on the available thermal store; in the winter this may only last for an hour, but this could be enough to resolve more minor problems. At Pimlico, the CHP engines take 20-30 minutes to restart and regain full operational capacity, fast enough for the accumulator to provide a seamless supply to its customers. Financial rebates are offered if there is more than 24 hours interruption of service, but these are very rarely needed as the thermal store provides the buffer required.

This report has outlined how thermal energy as a by-product of industrial process can be stored and used later. The Pimlico system uses waste heat from its CHP engines which generate electricity. Previous research [36] found, through a questionnaire survey, that the source of the heat made a difference to its acceptability. Waste incineration as a heat source was considered positively by nearly half of survey respondents (n=323). Coal and gas power stations as heat sources elicited a more mixed response (positively by 39% and negatively by 24%); Nuclear power as a heat source received a more negative response (24% positive, 43% negative) and biomass energy as a heat source received a very substantial neutral/don't know response, perhaps due to its relative unfamiliarity. Waste heat from industries was considered most favourably of all: positively by 67% and negatively by 10%.

The potential for a district heating system with a thermal store to bring a community together, through the sharing of a resource, was explored with the managers of the Pimlico system. However, there was a feeling that the heating system did not influence the sense of community. The provision of heating was seen as a part of their housing for which they paid individually.

5.5   Economic Impact

The introduction of a thermal store as part of a heating system offers a potential economic impact, through the requirements for initial installation and on-going maintenance. These will require new skills to be developed, including specialist knowledge, particularly in maintaining the system effectively and efficiently. The Pimlico system is carefully balanced to ensure that all properties receive adequate heat, despite their geographic dispersion. This means that any engineers working on the system need to have a good understanding of the impact of any changes they make, as these will be wide reaching. The Contracts Manager at

PDHU has created a targeted induction pack which he provides to all contractors working on the system. Actions can affect the wider system without a contractor realising, and so this induction pack (and on the job support from the engineering team at PDHU), provides a site-specific guide to the whole system. This is critical to enable the provision of heat to all the properties and passes on the experience of the system to others. It was felt that there is a lack of skills within the UK in being able to work on this type of complex system and the transfer of accumulated knowledge from the senior engineer to the more junior at Pimlico shows evidence of a succession plan, but highlights the risk in the system through considerable knowledge being retained by only one or two people.

The PDHU accumulator is an open vented system and is emptied and checked every 10 years. In previous years, the tank was emptied, stripped, repainted and refilled, at considerable cost each time; a cost that is ultimately borne by the residents. Following a failed use of epoxy resin as the coating material (which was found to blister and cause corrosion where water had seeped through), the system now uses no coating on the inside of the tank, but relies on the corrosion control chemicals used to treat the water, which also protect the pipework. As a result, the maintenance is easier and cheaper. At the top of the tank, there is some corrosion at the air-water interface. This could be resolved with the introduction of a nitrogen cushion, but this would add to the operational costs and introduce health and safety complexities which were not seen as being cost-effective.

The accumulator at PDHU is insulated with cork, then covered with a plaster finish. Whilst there are thermal losses, the cost of upgrading the insulation was not felt to be worthwhile. A visual inspection shows wear and tear damage to this plaster, although this is generally superficial (see Figure 20).

Figure 20. Superficial damage to the accumulator's plaster coating

The increase in numbers of thermal energy stores presents the opportunity for economic growth as part of their installation, operation and maintenance, although this may be balanced against a reduction in other heating systems. However, there is the opportunity for workers to retrain, developing skills and expertise in the new systems. The skills associated with the thermal stores are not likely to be significantly different to those required for the wider heating and power systems that the stores will service. However, these systems could require particular levels of expertise, particularly in understanding complex systems and the operation of large plant, as indicated by the staff at Pimlico. The system requires fine tuning to optimise its performance and this may require significant training and experience. If systems are run at sub-optimal levels, their benefits may be undone. With the limited number of thermal energy stores in the UK at present, expertise from elsewhere may be needed to initiate the market. However, once the technology is established, skills from within the UK will be developed effectively.

5.6   Behavioural Impact

A thermal energy store has the potential to buffer the provision of heat which could impact on behaviour in both positive and negative ways. The provision of a consistent supply of heat provides excellent service to a consumer, and could allow them to use their property more flexibly, if there activities do not need to fit with a regimented, routine supply of heat or power. This constant supply may, however, encourage people to use more energy, although this could reduce peak loads. Residents on the Pimlico housing estates have access to their heating and hot water for 17 hours a day (6am – 11pm) as the standard provision, which ensures their homes are warm all day and evening. The use of waste heat from other processes reduces the cost to the end user and the thermal store allows this heat to be used at a time when it is needed, rather than when it is supplied. Upham and Jones (2012) stress the need for district heating systems to 'fit in' with the existing routines and habits of users, if both systemic and contractual lock-in of a new system is to be achieved. A thermal store provides a flexibility to allow a range of behaviours that may not be possible with other systems without storage.

Properties served by the PDHU system, shown in Figure 21, are primarily multi-apartment blocks. As a result, they benefit from the heat transfer from neighbouring apartments. Whilst all properties are supplied with heating (and pay for this as part of their tenancy agreement), it would be possible to not heat a property and still keep warm from the surrounding building fabric. Other properties, particularly those with an exposed elevation have required additional heat and larger radiators have been installed. Secondary heaters (electric fan heaters) are used on occasion, but this practice is thought to be limited; there is no evidence of the use of air conditioning units to combat overheating. As a result, the provision of heating appears to meet the behavioural demands of the occupants. Heat loss is minimised from the external walls through cavity wall insulation and double glazing, although front elevations cannot be improved in this way as the estate is now a conservation area and so front doors and windows remain single glazed. Clearly, this is not an effective long term solution if carbon emission targets are to be met.

Figure 21. Properties served by the PDHU and its thermal store

There are no domestic thermostats installed in the Pimlico properties as there is block control of the heating, with a weather compensated variable control system. Residents do have the ability to open windows if they are too warm and a visual inspection of the windows has been used in the past to identify if the control systems are working effectively. This simple, but somewhat imprecise, approach could be enhanced by more sophisticated sensor technology to ensure end user needs are being met at a minimum system cost.

5.7 Built Environment Impact

Thermal stores can be very large and, if above ground, can have a significant impact on the built environment. They may take space away from the community, or change the local landscape. If planned sensitively, a thermal store can have minimal impact, allowing landscaping to hide an installation, or for good design to make it a feature. Residents at Pimlico see the thermal store, a 41m tower very close to their properties (see Figure 22), as

"an old friend" which they have accepted. It has architectural appeal and, together with six housing blocks, was Grade II listed in 1998. This shows the positive potential for design to enhance the introduction of thermal storage systems.

Figure 22. The thermal storage tower has architectural appeal

The design of underground thermal stores also needs to consider the impact on the built environment in relation to siting decisions. Whilst many can be covered with a layer of soil which can be replanted, they may restrict the inclusion of trees. At the Okotoks Borehole Thermal Energy Storage (BTES) Project in Canada [37], deep-rooted trees were permitted only in areas outside the borehole field, which affected the appearance of the surrounding environment.

5.8 Case Study 2 Conclusions

Information in this specific area in the literature is very limited and so evidence for this review has been drawn from expert knowledge and a case study of the Pimlico District Heating Undertaking in central London. Further work in this area is needed, including more extensive qualitative reviews of existing systems to fully understand the issues.

Thermal energy stores offer a number of non-technical advantages. The ability to balance a variable supply and demand ensures that all businesses and residents on the system can be provided efficiently with heat and hot water to meet their needs. A thermal store also offers an emergency buffer to ensure seamless supply in the event of planned or unexpected maintenance. This ensures that the most vulnerable members of the community are also provided with heat and hot water. This can improve living conditions, reducing damp and hence mould growth, and generally improve levels of thermal comfort. In a district heating system such as the Pimlico District Heating Undertaking, heating provision can be adjusted centrally to ensure these standards are maintained even in very cold winters at a fixed and known cost. However, this cost is inflexible and so residents are not able to adjust their expenditure according to their income, but the delivery of more efficient heating or supplementing those on lower incomes could provide an effective way of ensuring those in fuel poverty are provided with adequate heat and hot water throughout their property.

There is a potential skills gap in managing and operating complex systems with thermal stores. Initially, these skills may need to be imported, but the UK has the capacity to develop appropriate skills quickly. The inclusion of thermal storage as part of the UK energy system provides an opportunity to develop new skills, but will inevitably reduce the attention on disaggregated heating systems.

It is important that thermal storage systems are sympathetically introduced to the built environment, to ensure they are accepted by the local community. Good design can ensure that the impact on the local environment is positive.

The thermal store at Pimlico District Heating Undertaking produces better control; without the thermal store, the system would need to vary in operation to meet the changing demand, and so run inefficiently. As the lead engineer commented: "When you are dealing with literally millions of pounds worth of heat each year, those differences do matter".

Acknowledgements

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Abstract

Smart Home technology looks set to become an increasingly common feature of domestic life. However commercial desire for technical innovation rather than explicit user needs are often the driving force behind the development of Smart Home products and services. This study adapts the Cultural Probe approach developed by Gaver *et al* [2] to collect primarily visual data about what people value within their home environment. Whereas Cultural Probes are predominantly used to build empathy with users when designing product concepts, this approach attempted to provide similarly fun and engaging prompts for data collection when the design process and project context required more structured consideration of user needs. This paper presents the method developed, project findings and recommendations on how the method should be applied.

Keywords

Introduction

This study was conducted by the Ergonomics and Safety Research Institute (ESRI) at Loughborough University as part of two large technical programmes under The Application Home Initiative (TAHI), with matched funding from the UK's Department for Trade and Industry. These programmes developed and trialled two prototype Smart Home systems: one to improve energy monitoring and equipment management in the home (Equipment Management Trial); the other to provide aggregated information, energy monitoring and entertainment services to the householder (Services Aggregation Trial). ESRI's role in both projects was to provide human factors support within a technology driven development process [1]. Product concepts were already determined at the start of the projects by the technology providers within each project consortia. Both projects focused upon the development of technical solutions that integrated off the shelf and innovative technologies in order to demonstrate the commercial and technical feasibility of providing Smart Home services within existing (rather than purpose built homes). (For clarity the two projects will be treated as one within this paper as ESRI's role within both was essentially the same).

Although ESRI's role mainly involved designing and evaluating user interfaces for the emerging equipment and services, the authors wished to take the opportunity to promote User Centred Design amongst the largely technology focused project partners. This paper describes a Photo Study method to record the domestic context inspired by the Cultural Probe approach of Gaver *et al* [2] developed to meet the demands of such a technology driven development process. The goal was to convince the technical partners that users do not always share their views concerning the value of Smart Home technologies and that many of the behaviours currently used to organise daily living do not require advanced technologies to succeed. The aim was not to push a Luddite agenda, rather to help technologists understand where technological solutions are currently valued by consumers and to highlight domestic contexts of use where products must particularly meet the emotional as well as functional needs of users in order to be valued and accepted. The method is described and its strengths and limitations discussed in relation to the project context. The appropriateness of applying a Probe approach within a technology focused design process is then discussed and conclusions drawn about the wider applicability of the method.

Background

In contrast to the more extensive body of literature on the social context of computer use in the workplace there is little written on the social context of computer use in the home [3]. Work by Venkatesh [4] introduces the idea of two key constructs - the social space and the technological space - which define the main parameters of household-technology interaction. The computer industry has a strong interest in integrating computer technology into the home, yet there are few sources of knowledge on how this works and fits in practice [5]. Many technology providers have sound knowledge of the technology they produce but not of the social context of its use [4,6]. Visions of what technology can do for people are rarely based on any comprehensive understanding of needs and in some cases are blatant technology push [7]. When technology is incorporated within the home, the people who live with the technology on a day-to-day basis have tended to have been overlooked [7,8].

We wished to examine the home environment as a social space in order to understand the role technology plays within everyday household activities and interactions. In particular the study was designed to explore the perceived value of technology in the home – in what use contexts was technology valued and why? What did this tell us about the likely acceptability of the Smart Home solutions being developed within the project and how should this understanding of user needs drive the development of future Smart Home products and services? Gaver [9] states that unless people start to respect the full range of values that make us human, the technologies we build are likely to be dull and uninteresting at best, and de-humanising at worst.

A number of factors drove the development of the chosen approach:

- An engaging data collection approach was required that respected the privacy of the householders and encouraged individuals to take part in the study during their leisure orientated time at home.
- The opportunity to conduct extensive user studies was not provided by the project structure. A 'discount' method was therefore needed that fitted the resources and timescales of the project.
- The output of the method needed to be in a form that was meaningful to the technology focused project partners who mainly had engineering backgrounds.
- The authors wished to refresh their own enthusiasm for engagement with users within a project that was facing numerous technical challenges relating to the task of integrating diverse technologies within the home environment.

Many observation based studies carried out in domestic settings adopt an ethnomethodological approach drawing upon techniques developed within the domain of computer supported co-operative work (CSCW). However researchers from the CSCW tradition admit that even "quick and dirty" ethnography [10] that typically involves the researcher spending several days continuously present within the workplace is unlikely to be acceptable to many households. "A pragmatic as opposed to methodologically-purist stance" [11] to data collection is therefore required in order to investigate the home environment. Investigating the use of technology in the home requires trust to be established between researchers and participants [12]. Even when trust is established, O'Brien and Rodden [13]

acknowledge that many aspects of the domestic routines are too personal to be observed. Crabtree and Rodden [14] argue however that it is a misconception to view the home as a particularly difficult domain to observe through first hand observation and in fact workplace studies can raise greater barriers to data collection. Access to the home rather than the workplace can be simpler to negotiate and there are typically less political issues to be managed. Once the acceptance and trust of study participants has been gained, they report from their own research experiences that people are surprisingly open to being directly or indirectly observed (e.g. using video cameras) within the home environment. However gaining the acceptance and trust of study participants takes time and requires flexibility within the study design. Crabtree and Rodden (2004) describe how the location of video cameras and recording times had to be negotiated with study participants during a longitudinal study of household activities. They also report that when a subsequent set of participants were asked to video and log the flow of communications in and out of the home, that not all details were reported because of "a variety of sensitive household matters". Therefore Crabtree and Rodden, whilst rightly cautioning against exaggerating the demands of home based research, still affirm the need for methods that allow participants some degree of control over data collection.

We wished to counter such privacy concerns by placing data collection firmly in the hands of the study participants. The use of a data collection method based upon the Cultural Probes approach of Gaver *et al* [2] appeared at first glance to meet our need for a self-administered and engaging data collection tool. However the context for applying Probes within our project was very different from the artist / designer research context of Gaver *et al* and actually contrary to the design culture that they are looking to embody within the Cultural Probe approach (Gaver *et al* 2004). A further research question therefore arose – can Probes be used usefully beyond concept design to stimulate consideration of user needs within a technology push development process? In particular can the subjective and emotive responses generated by Probe tasks be systematically analysed in a meaningful way to facilitate the assimilation of the Probe outputs by technologists who prefer informative rather than inspirational guidance?

The Cultural Probe approach was developed to "provoke inspirational responses" from elderly users within the EC Presence project [15]. Gaver *et al*'s [2] Probes consisted of a package of maps, postcards, cameras and other materials that were taken home by the study participants to fill in or use and then send back to the project researchers. The materials were deliberately aesthetic, attractive and provocative in order to stimulate the users to think about their lives in unconventional ways. The Probes were introduced to the study participants as a way for the designers to get to know the users and for the users to get to know the designers. The intention was to provide insight into the culture and values of the target user population in a way that countered any stereotypes held by the designers and researchers. Gaver *et al* [2] describe how the Probes were not intended to provide an objective account of the users' needs, nor were they intended to define a set of problems. Instead the Probes were intended to create an "impressionistic account" of the users "beliefs and desires, their aesthetic preferences and cultural concerns."

The concept of using design-orientated user research tools based on self-documentation ('Probes') has been extended by others to meet a much wider range of research requirements. Mättelmaki [16] provides four reasons for applying Probes based on a comprehensive review of Probe based approaches: to provide inspiration, information, participation and dialogue. Gaver's Cultural Probes are according to Mättelmaki an example of 'inspiration Probes'. Objectivity is avoided when analysing the inspirational Probe responses; instead the raw Probe data are used in a "designerly way" to create personas, frame problem spaces and capture design ideas.

Information Probes are used more directly to elicit information about user needs. The information Probe tasks are primarily descriptive and leave less room for interpretation than the Probes for inspiration. Information Probes were used by Hemmings *et al* [17] to analyse user needs for future systems designed to support patient care within a sheltered housing complex for former psychiatric patients. The Probe tasks were used in preference to observation based methods as being watched was likely to be unacceptable and potentially damaging for those with paranoia and related conditions (see also Rouncefield *et al* [18]).

Mättelmaki also describes how Probes can be used within Participatory Design (e.g. Muller [19]) to provoke users to use their imaginations, express their ideas and think more widely about possible solutions for their needs. Both inspirational and information Probes can be used to facilitate the participation of users in design. Hutchinson *et al*'s [20] Technology Probes, used to provoke users to consider their needs for remote interaction with others, are an example of information Probes being used in this manner. Mättelmaki's final role for Probes is to facilitate dialogue between users, researchers and designers. Hemmings *et al* [17] saw their information Probes as an opportunity to build trust with the hostel residents using the delivery and collection of the Probe toolkits as part of this process.

Gaver *et al* [21] express concern about Probes being used beyond their original inspirational context: "People seem unsatisfied with the playful, subjective approach embodied by the original Probes and so design theirs to ask specific questions and produce comprehensive results. They summarize them, analyze them, even use them to produce requirements analyses." Analysing Probe responses, they argue, raises the following concerns:

- Asking unambiguous questions reduces the likelihood of receiving surprising answers that can inspire innovative thinking.
- Summarising results leads to consideration of average users which can also lead to the loss of inspiring individual detail.
- Presentation of analysed and summarised results to designers instead of raw data reduces exposure to the users' world.
- Attempting to justify the Probe returns in scientific terms constrains imaginative engagement with the outcomes.

In particular they are concerned that the Probes used in their original form embody an approach to design that encourages "subjective engagement, empathetic interpretation and a pervasive sense of uncertainty as positive values for design". Adopting a scientific approach to using Probes is perceived by Gaver *et al*. as contrary to their original concept. Mättelmaki, although more comfortable than Gaver *et al*. with the concept of information Probes, also concludes that Probe outputs are difficult to analyse in any systematic way and therefore often unsuited to meeting the demands of product development encountered beyond the concept design stage. When concrete answers are required to specific questions,

she concludes that Probe tasks are often too unfocused, subjective and emotional. Probes are therefore best applied within the early concept design phase where objectivity and systematic analysis of needs are not the priority.

Whilst accepting that we were losing much of the essence of true "Probology" [21], our research needs were still felt to justify a Probe based method of data collection. Most significantly this approach provided the opportunity to explore whether highly visual and subjective Probe outputs could be systematically analysed in order to provide more structured and informative output suited to the technology focused culture of the project.

Method

The study participants were issued with mission packs, shown in Figure 1, which contained all the resources they needed to complete the Probe tasks. The packs were designed to be stimulating and fun to complete yet structured to constrain data collection to the specific needs of project. The pack included:

- A participant information sheet
- Photograph record book
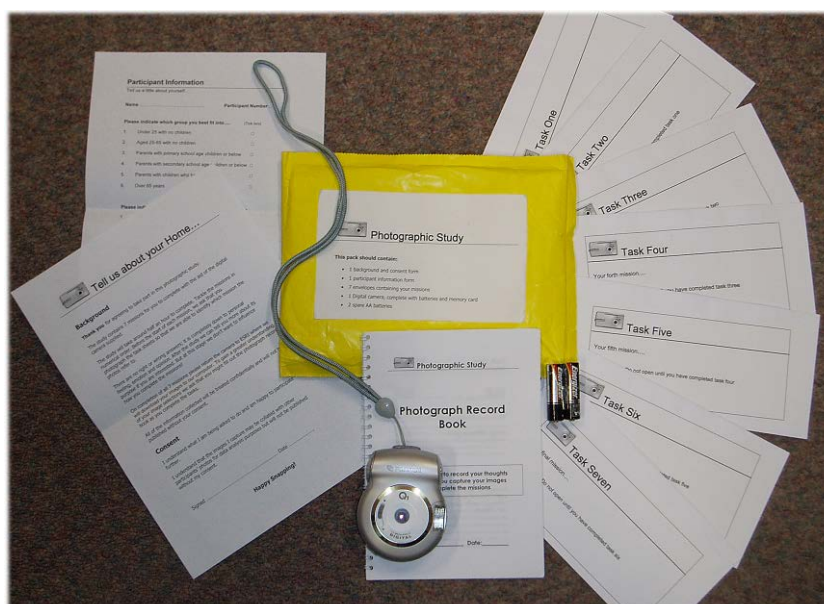- Seven sealed mission envelopes
- Digital Camera and spare batteries

Figure 1. Photo Study Mission Pack

Participants were not informed of the study's detailed aims, instead they were briefed on a broad 'values' study and were asked to complete 7 missions to capture images in and around their home. This provided a structured enquiry approach, where participants where free to take images of anything within their home, but within a structured framework. The missions were developed to standardise the context of the photographs, and included issues derived from previous focus group research within the project and the interests of the technology partners. Participants were instructed to complete each mission before going on to the next. This prevented participants modifying their answers to a mission in light of subsequent missions. They were free to take less than the requested number of photographs for each mission if they could not find images to suit. They were also allowed to take photographs of the same item for more than one category if required.

The missions were:

1. To capture images of the 5 things you value most about your home.
2. To capture images of 5 things about your home that save you time.
3. To capture images of 5 things about your home that make you feel safe and secure.
4. To capture images of 5 places where you display information in the home.
5. To capture images of 5 ways you share information with others in the home.
6. To capture images of 3 pieces of technology that you like using, and 3 pieces of technology that you don't like using in the home.
7. To capture images of 5 things you currently do in your home to save energy or help the environment.

In trialling the study packs with participants' own digital cameras, it was found that the clarity of some of the images was such that the finer details of letters, bank or credit card statements and emails captured within the images could be easily defined. Participants were left feeling quite vulnerable and uncomfortable about sharing the images with the researchers. To overcome this, a digital camera with low resolution image capture was purchased specifically for the trial. The camera was chosen for its fun design and simple 'point and shoot' functionality. As they conducted their missions, participants completed the photograph record book, noting down their image selections and a brief explanation of their choices. A total of eight people participated in the study (5 male, 3 female) recruited

from the local population. They all had a limited knowledge of Smart Home technology and were considered to fall into the target market group for the TAHI trials.

Analysis Approach

Gaver *et al* [21] deliberately avoided systematic analysis of the outputs from their Cultural Probes. As already described, the technical focus of this project required more structured output from the study. Content Analysis provided a practical method for analysing images that did not require the involvement of participants. Krippendorff [22] describes Content Analysis as "making replicable and valid inferences from data to their context". Whilst more usually applied to written documents, Content Analysis is used to analyse images, and was felt suitable for analysing the study outcomes as there was both context (the missions) and content (the photos themselves). When performing a Content Analysis, the recording unit is defined, e.g. themes that occurred within a text, and the output is analysed in detail by noting the occurrence of each theme. Once this is complete, the data can be analysed in various ways. As it is likely that some degree of inference may be required by the researcher [23] more than one independent analysis of the data is recommended and was performed.

The photographs for each mission were sorted into groups of like content, for example, pictures of windows and door locks; pictures of people; pictures of telephones (see Figure 2), and a tally of each category was recorded. A total count was also made of how many pictures for each mission were technology-based, as this was a main focus of the research. This approach has similarities to affinity diagramming [24] which can be used for organising the structure of a new system or uncovering the hierarchical structure in a set of concepts. Designers or users write down potential screens or functions on sticky notes and then organise the notes by grouping them and by placing related concepts close to each other. The categorisation described in this paper provided a simplified version of this.

Figure 2. Photo Study Content Analysis

The analysis was conducted by two human factors experts, (with reference to the record books where further clarification of the photographs was needed). A third person carried out a further classification activity to produce a single grouping and set of categories, based on the findings of the first two researchers. Where there was significant discrepancy between the opinions of the researchers, the photograph was discussed and a consensus opinion was arrived at. This draws on the validation techniques used in the development of warning symbols, where the meaning of a warning is judged by a panel in this way [25].

In summary, the main steps in the method were as follows:

1. Pictures for each group were printed and separated.

2. Two analysts took each group and 'card sorted' them into categories and gave each category a name.

3. Each group was categorised as technology related and non-technology related.

4. A third person reviewed the categories and produced a single set to regroup the items appropriately. Consensus was reached where there was significant discrepancy.

5. For some groups more general categories were produced.

6. Each final groupings were reviewed to highlight contextual factors relating to future products.

Results

The observations and results from each of the missions are presented in the following sections. The photos captured for the first mission are reproduced as a collage; for the remaining missions, a selection of images only is presented, together with comments about the images from the analysis of the data. Results of the Content Analysis are presented in overview in Tables 1 to 7, together with the percentage of images considered to be 'technology' and 'non-technology'. For the purpose of this study, items of 'technology' were regarded as those containing electrical, electronic or computer components.

Things you value most in your home

The full collage of images collected for this mission is presented in Figure 3.
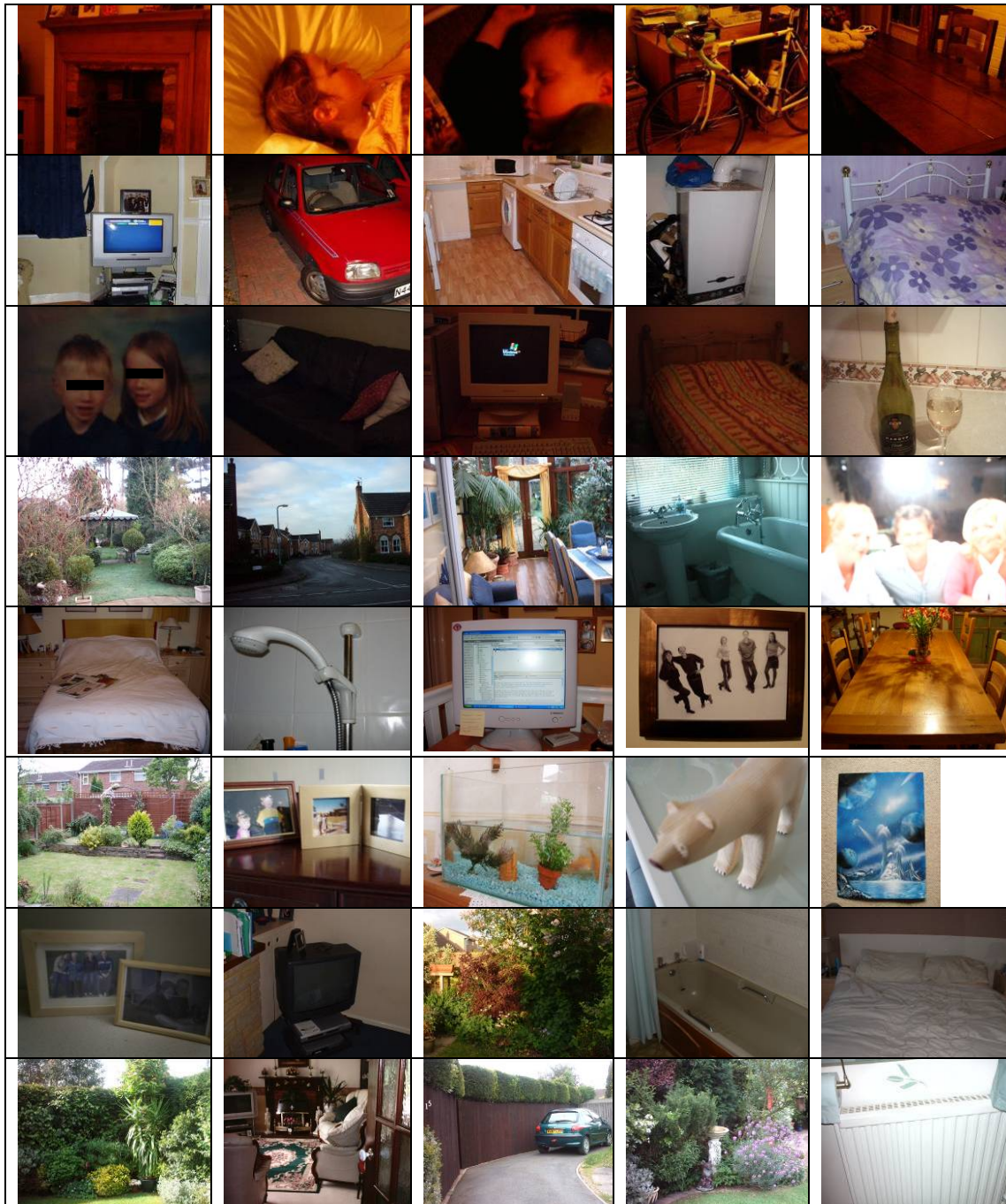
Figure 3. Values images

The participants valued people (in particular family), space and memories most highly. Image selections were consistently associated with terms of comfort, relaxation and sentiment. Of the technology that appeared in the photos, it was the services they provided rather than the physical devices that were valued. For example, the TV was valued for the entertainment it provides and the computer for keeping in touch.

Very little technology was photographed for this mission. The number of images that could be considered technology-based was 17.5% (7/40) (see Table 1).

Table 1. Content Analysis results - Things you value most

Relaxation/home comforts	12	Technology	7	17.5%
Family	7	Non-technology	33	82.5%
Garden/neighbourhood	6			
Living/social space	5			
Appliances	4			
Cars/bikes	3			
Objects/Art	2			
Pets	1			
Total	**40**		**40**	**100%**

The minor value people placed on technology provided a reminder to the authors and some evidence to the other, technically focused, project partners that, for Smart Home technology to be effective, it must meet the needs and values of the end users. Simply providing a technological solution and expecting people to value it is unlikely to be successful.

Saving time

Figure 4 shows a selection of images taken in response to this mission. The returned material contained images depicting mainly technology and automation of household chores, in particular preparation of food and washing of dishes and clothes. Other images captured ways of organising things; for example a mug tree, key hooks, a weekly planner.

Figure 4. Saving time images examples

Clearly technological products have an important role in saving people time in the home. The biggest breakthroughs in terms of time saving are in completing 'household chores' such as washing, cleaning and cooking. However it is interesting that PCs and IT products are

not seen as time saving. Perhaps this highlights an opportunity for future product developers. Remote access to appliance control and centralised access to aggregated services were developed for later testing in the project, both of which potentially saved the consumer time and were well received by the users.

Table 2. Content Analysis - Things that save you time

Cleaning/washing/tidying	18	Technology	33	85%
Cooking/drinks	9	Non-technology	6	15%
Comfort/hygiene	3			
Entertainment	3			
Information/communications	3			
Transport	3			
Total	**39**		**39**	**100%**

Safety and Security

Figure 5 shows a selection of images in response to the safety and security mission. Most of the returned material could be summed up as 'lights, locks and a line to the outside world'. Several people pictured their partner/spouse or a family member, as they invoke feelings of protection and safety.
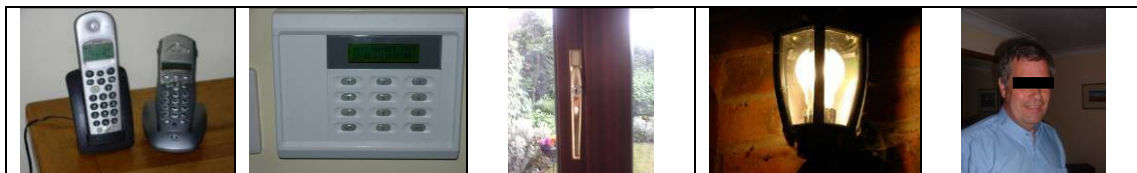
Figure 5. Safety and Security image examples

Most objects photographed had a highly visible presence in the participant homes, for example blinds on windows and bolts on doors. Although this may be the result of the visual nature of the task, it might suggest that smoke alarms and carbon monoxide alarms are things that run in the background of the home and are therefore taken for granted, however conclusions should be verified through further research. The terms 'safe' and 'secure' have a broad scope and so participants may have focused on one or other of the terms rather than capturing images that represented both. This illustrates a limitation of the approach, where intentionally little guidance was given to allow participants to make their own interpretation. Technological products are still in the minority compared with barriers such as strong locks,

doors, and windows. People may see intruders as a greater hazard than gas and carbon monoxide poisoning. Ways of obtaining help either from other members of the family or by seeking help over the phone is seen as having an important role. It may also reflect the poor trust many people have in the reliability of technology, reflected in other aspects in the project's research. Smart Home safety and security solutions may not be trusted unless demonstrated to be dependable and designs could incorporate appropriate feedback to reassure the consumer.

Table 3. Content Analysis - Things that make you feel safe and secure

Barriers	14	Technology	14	36%
Alerts/Alarms/Deterrents	14	Non-technology	25	64%
Communications	5			
Human support	5			
Automatic cut off	1			
Total	**39**		**39**	**100%**

Displaying information in the home

Figure 6 shows a selection of images in response to the displaying information in the home mission. Information was consistently shown displayed on notice boards, fridges, by the front door and on sideboards and mantelpieces. Messages are left in different locations chosen because they are integral to the everyday routines of the householders and therefore unlikely to be overlooked. For example, a note left on the stairs to ensure that it is seen as someone walks in the front door or a note left by the kettle so that it is seen in the morning. This finding confirms those of Crabtree and Rodden [14] and Taylor and Swan [26] and supports the need for ubiquitous Smart Home solutions that support the customisable display of information around the home rather than attempting to impose centralised information displays upon the existing household routines of users.

Figure 6. Displaying information in the home image examples

Table 4. Content Analysis - Places where information is displayed

Electrical/Electronic	16	Technology	15	38%
Handwritten note	10	Non-technology	24	62%
Diary/calendar/chart	8			
Highly visible place	5			
Total	**39**		**39**	**100%**

Sharing information

Figure 7 shows a selection of images in response to the sharing information mission.

Figure 7. Sharing information image examples

It was interesting to see that hand written material is still a predominant way of sharing information with others. Apart from the phone and computer to communicate externally, electronic devices are hardly used to share information in the home. Again this may be an opportunity for future developers of Smart Home products. Mobile and landline phones are a popular way of sharing information and featured in much of the returned material for this mission. Images of household calendars and diaries and notes left in different locations around the house again reflected other research findings [18, 26].

Table 5. Content Analysis - Ways in which you share information with others

Hand written	20	Technology	13	32.5%
Indirect personal	8	Non-technology	27	67.5%
Printed	5			
Electronic display	4			
Personal	3			
Total	**40**		**40**	**100%**

The images for displaying and sharing information generated from Missions 4 and 5 showed a number of consistencies (e.g. telephones and calendars were included in the photos sets from both missions). Although the two concepts are similar, the missions were addressing different issues. Mission 4 asked for images of where information was displayed and Mission

5 asked how information was shared. Information was displayed where it was most likely to be noticed or not forgotten by the users which, as previously discussed, warns against the introduction of centralised information displays. That half the images depicting how information was displayed showed handwritten notes suggests that users value speed and flexibility when creating information for personal use or for others. Therefore technology solutions that offer potential communication and organisational value to users (for example shared home calendars that can be accessed both from fixed and mobile devices) must also offer rapid and flexible data capture if they are to realistically compete with scribbled notes created by users following the 'path of least resistance'.

Technology likes and dislikes

Figures 8 and 9 show a selection of images of technology likes and dislikes.

Figure 8. Technology likes image examples
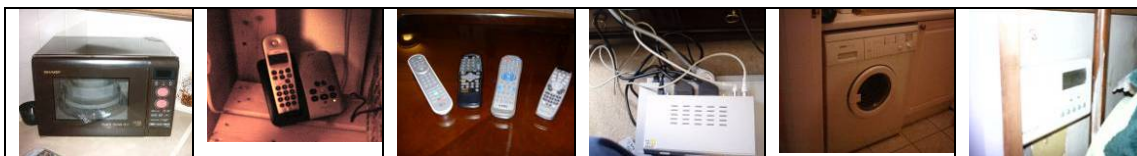
Figure 9. Technology dislikes image examples

Technology likes and dislikes were mainly down to personal choice and the device under judgement. The item types for dislikes was more widespread than for the likes indicating that there is a still a broad scope for ergonomics in the design of consumer devices in the home. While the traditional problem of video programming was evident, it was interesting that there were a large number of audio visual entertainment devices under likes indicating the development of this area towards creating very acceptable and desirable products. Images of wires from the back of the TV/VCR and arrays of remote control devices among the dislikes suggested the aversion people have to the combination of devices and the complexities of networking, rather than a dislike of the specific device. Principles of keeping

interfaces simple and consistent were reaffirmed and the authors ensured common interface layouts and navigation systems were included in the development of the Smart Home devices within the project.

Table 6 – Content Analysis - Items of technology you like or dislike

Likes		Dislikes	
TV / VCR / multimedia	7	Telephone	4
Telephone	4	TV / VCR / Multimedia	3
Computer	3	Remotes – too many!	2
Microwave/cooker	2	Washing machine	2
Remote control	2	Cables at back of TV	1
Washing machine	2	Clock radio	1
Burglar alarm	1	Computer printer	1
HiFi	1	Digital Camera	1
Radio	1	Hair straighteners	1
Waste disposal unit	1	Heating controls	1
		Hedge trimmer	1
		Hi Fi	1
		Microwave	1
		PDA	1
Total	**24**	**Total**	**21**

Energy saving behaviour and helping the environment

Figure 10 shows a selection of images in response to energy saving and helping the environment mission.

Figure 10. Energy saving and environment image examples

Local authority refuse collection techniques prompted participants to capture the recycling bins and boxes featured in many of the photographs, suggesting that recycling now appears to be an accepted part of daily life (within the sample). There appears to be scope for more use of technology to help the householder be more 'green'. Any such device to help in, say, recycling would need to be simple and convenient to use if it is to be accepted as a convenient product or process.

Double glazing, energy saving light bulbs, switching lights off, using economy settings on domestic appliances, putting lids on sauce pans and turning down the thermostat also featured in the material returned for this mission.

Table 7. Content Analysis - Ways to save or help the environment

Recycling	11	Technology	6	15%
Turning down settings	5	Non-technology	34	85%
Heating thermostat control	4			
Boiler /tank	3			
Low energy light bulbs	3			
Switching electrical things off	3			
Double glazing	2			
Pan lids	2			
Using shower	2			
Other	5			
Total	**40**		**40**	**100%**

This mission provided the lowest technology related images. Smart Home technology can offer conflicts between the cost of delivering the technology and the savings it creates. Clearly, any environmental or energy saving device must be obviously 'green' in itself, not just in the functions it performs.

Discussion of the Approach

From the collages alone it is possible to see, at a glance, that this method provided an interesting range of responses to the missions. However, in order for the method to have value to support other approaches, it is necessary to consider how well it met its objectives. Each of these is discussed in turn.

Provide a discount method for gaining an understanding of the value and use of technology in different domestic contexts of use

Although the authors' approach was tested at a different stage of the design lifecycle to the "fuzzy front end of design" [27] where Probes approaches have most to offer, the results showed that it can play a useful role in identifying design implications when the design concepts are more established. The Photo Study offered a cost and time effective alternative to ethnographical methods as it did not require researchers to visit participants' homes. For the purposes of the study, it was possible to gain some insight into the range of

ways that people responded to the mission questions. The stripped-down version of the Probe technique was effective at allowing an initial analysis of the photographic data, without significant supporting information. The conclusions that can be drawn from the photographs alone are limited, but they are felt to be extremely powerful in response to the stated research questions. In answer to whether people value and use technology in different ways, then it is possible to see the diversity of responses, even with the limited sample used in this study. If the purpose of the research is to identify what might overcome the barriers that may be present, then additional, supporting techniques are needed. Mättelmaki and Battarbee [28] found that asking participants why they chose to create particular photos or other Probes provided responses that led to a deeper understanding of user needs that could not be gleaned from the photos alone. The photo record books, not analysed as part of this study, would provide some additional reasoning behind people's choices of photograph. This should be supported further by individual interviews or focus groups to explore particular issues where time and resources allow.

Gain an insight into people's lives in an unobtrusive way

The Photo Study allowed the participants to be in control of the data they provided. This overcame some of the sensitivity issues often present when collecting data in the domestic environment. The researchers felt they had been given a window into the home in relation to the particular missions, however, the study did not seek to validate this and so it is not possible to identify if someone had shown an accurate or representative picture of themselves. Indeed, it is unlikely that this level of insight could be gained through this method alone.

Provide human factors researchers with inspiration and information on which to develop further Smart Home designs

In common with other uses of Probe studies [16], the Photo Study provided the human factors researchers with further evidence of the diversity of people's lives and homes and how technology is valued and integrated into their homes. Understanding this diversity is key to ensuring that new technology introduced into the home is acceptable to everyday consumers as well as early adopters. This method provided an effective and efficient way of reminding the researchers of the diversity of domestic life whilst the structured analysis of

the study responses enabled the researchers to begin to make sense of this complexity so that meaningful contributions to design could be offered to the technical project partners.

Provide technical partners with insight into end users' views of technology

Although the Photo Study worked well as a tool for structuring the thinking of the human factors specialists within the project, it is less clear whether it was effective at providing insight for the technical partners directly. Informing the design of Smart Home technologies within a technology dominated design culture can be difficult, and a technical partner might not fully appreciate the subtleties of the images, although the overall effect of the collages was undeniably powerful. The study aimed to highlight to technologists that everyday consumers do not view or use technology in the same way that they do. Therefore over-specified products for doing simple household tasks are unlikely to be acceptable, when the users already have perfectly good, non-technological ways of doing things. However, the findings also show that a good deal of technology is already in people's homes in the form of domestic appliances and that technology is valued by users when it saves them time and effort. At this level the study met its aim and by providing quantifiable output, helped the technologists come to terms with what are normally unquantifiable issues relating to users' attitudes, values and behaviours in the home.

General tips for applying method

It is useful to use card sorting to group the pictures into meaningful categories. This was facilitated by printing each picture out as a single small image. It is recommended that at least two analysts separately classify the images and then work together to form a consensus both in terms of grouping and group naming. This paper particularly explores the value of the visual images independently of the data contained in the record book and for this reason the images were analysed without significant recourse to the record book data. However in retrospect, it was felt that a greater depth of understanding could have been achieved by analysis of the record books to ensure the exact meaning of the photo taken was understood; for example, a photo of a treasured item reminding the owner of an enjoyable holiday, rather than just being an attractive trinket. This could be facilitated by replicating the associated user comments on the back of each photo.

Use of the mission format is highly recommended. The packs and sealed mission envelopes intrigued the participants and also broke the study down into manageable activities that could be fitted around other demands in the home such as children and cooking. This made the study less daunting and reduced the likelihood of data collection being put off by the participant until they could see a clear chunk of time to complete the study in one go. The use of the sealed sequential mission envelopes is also recommended as it did prevent participants reformulating their answers in relation to the previous questions.

Although the approach gave the authors the confirmation of user diversity they required, greater involvement of the project team would have been worthwhile. This could include a participative approach to the categorisation of the photos, allowing the technical partners to arrive at the themes and involving them with the detail of the approach, rather than just being presented with the results. It would be interesting to see how different stakeholders in a multi-disciplinary project team would categorise images and it is felt that a greater richness of understanding on all sides would be achieved.

Conclusions

Key findings from this study include:

- People value people, space and memories most highly, rather than technology or physical possessions.
- The items valued most highly were consistently associated with feelings of comfort, relaxation and sentiment.
- Technology and automation are viewed as saving people time and making household tasks easier, rather than adding value.
- Some participants captured images of places or objects that focused on pride, appearance and prestige. Smart Home technologies may invoke the same feelings in some users and, in this way, find their way into people's values.
- People do not display and share information in one single place or using one single technique; people often leave impromptu notes and messages left in context-specific locations around the home. A single, all-encompassing user interface can not adequately support this type of behaviour.

Smart Home technology looks set to become a feature of people's lives, whether it is wanted or not. The availability of technology and development of services with commercial benefits often means that the needs of the end user are treated as secondary. This study, through its novel approach to handling visual data collected using a modified Probe method, aimed to identify what people valued in their home environment. The use of this low cost technique, which involved a structured enquiry, allowed participants to show where technology was of value to them, and where it was not. The Photo Study was felt to provide excellent insight into people's home lives in the areas researched. It is not clear whether this could be translated to a wider survey where missions explored more sensitive issues, but it was a cost-effective exploration which participants enjoyed completing.

Content analysis of the visual data collected using the Probe based approach allowed meaningful reflection upon the role currently played by technology within the home environment in a form appropriate to the needs of the project's technology push development process. Whereas researchers and designers during conceptual design wish to be provoked and surprised, during the product specification stage of the development cycle there is a need for tools and techniques that structure the diversity of everyday life and facilitate the translation of user needs into product requirements.

The findings from the Photo Study have implications for the design of future Smart Home technologies and should be carefully considered in order that the consumers' needs are not overlooked within projects striving to overcome considerable technological challenges, particularly in a technology driven project. The home is a treasured possession where people feel secure and comfortable and solutions must be empathic to the home environment.

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Abstract

CALEBRE, a four year research project, is developing technologies to improve the energy efficiency of solid-walled housing in the UK, particularly in the owner occupied market. The engineering partners within the project require very specific information from user centred design (UCD) practitioners in order to develop innovative technologies. However the project recognises that it is the 'soft factors' that must be addressed in order to make these measures acceptable and appealing to householders. This requires a deeper understanding of users' motivations for improving their homes and the complex interplay of factors relating to aesthetics, lifestyle, life events, energy efficiency and finance. This paper presents how a practice-orientated UCD approach was taken to inform an engineering-driven product development process. It describes two data collection methods used within CALEBRE specifically to address these challenges and focuses on the specific home improvement practice of replacing windows.

1 Introduction

CALEBRE, a four year UK research project funded by Research Councils UK and E.ON, aims to establish a validated, comprehensive mechanism for reducing UK domestic carbon emissions within solid-walled housing that is acceptable and appealing to users. The project takes the approach of identifying, from a user perspective, the barriers and key challenges to the deployment of retrofit carbon-reduction technologies, and then by using the knowledge gained through householder engagement and surveys to appropriately modify selected technologies for field-trialling and user evaluation including thermal comfort evaluation. The selected technologies include electric and gas-fired heat pumps, home ventilation heat recovery, energy-efficient vacuum glazing and innovative advanced surface treatments to control temperature and moisture via nano-technology (Vadodaria, *et al*. 2010).

The CALEBRE project is focusing on older properties (pre-1930) in the UK which were constructed with solid (as opposed to cavity) walls. These are often referred to as 'Hard-To-Treat' homes, as they offer significant challenges for energy saving. The growth in housing during the late 19th century has meant that the UK presents a unique challenge in addressing its solid -walled properties. The project is also focusing on owner-occupied homes (homes that are lived in by their owners, who are therefore responsible for, and have to fund, any upkeep of their home). According to the English House Condition Survey 2007, 15.5 million homes in England are owner-occupied, with 29% of these homes (4.5 million) having non-cavity walls. The UK Energy Research Centre's scenarios for the UK energy system in 2050 anticipate that significant energy efficiency measures will need to be introduced to homes in combination with behavioural changes in order to meet the UK Government's carbon reduction targets (UK Energy Research Centre 2009). Given that up to 75% of the UK housing stock that will exist in 2050 is already constructed (Boardman, *et al.* 2005), understanding how to maximize the energy savings achieved through retrofitted measures is essential if carbon reduction targets are to be met. This requires an understanding of the process by which home owners undertake home improvements and their motivations to do so. It also requires an understanding of everyday practices, routines and lifestyle choices in order to ensure that the energy efficiency methods developed are acceptable and appealing to consumers.

A specific objective of the CALEBRE project is to establish, from previous research and a platform of user investigation, the socio-technical challenges to be overcome in developing appropriate technologies capable of inclusion within an integrated package of measures for reducing UK domestic carbon emissions from the existing solid-wall housing stock in the short to medium term. The research described in this paper formed a part of the 'platform of user investigation' with the specific aim to identify whether an understanding of home improvement practices could be translated into a form suitable for use by technologists within the context of the CALEBRE project. The intention was not to develop or challenge practice theory but rather to better inform exploration of the problem space. A case study is presented, within which the particular challenges associated with using a practice-orientated User Centred Design (UCD) approach in this context are described. It also introduces the data collection approaches developed within CALEBRE to address these

challenges. A specific example of replacing windows as part of the home improvement practice is discussed in more detail.

2 Applying practice-orientated methods within user centred design

UCD is a design philosophy that seeks to ensure that the needs and wants of users are considered throughout the product design process (Norman 1998). The long established premise for UCD is that an early focus on user requirements leads to the design of useful, useable and desirable products. The principles of UCD (Gould and Lewis 1985) are generally accepted to be an: early focus on users and tasks; empirical measurement; and iterative design. Preece, *et al.* (2002) suggests five further principles that expand and clarify the first principle. These are:

- Users' tasks and goals are the driving force behind the development.
- Users' behaviour and context of use are studied and the system is designed to support them.
- Users' characteristics are captured and designed for.
- Users are consulted throughout development from earliest phases to the latest and their input is seriously taken into account.
- All design decisions are taken within the context of the users, their work and their environment.

This last point does not necessarily mean that users are actively involved in design decisions but designers should remain aware of user requirements when making design decisions. Preece *et al.* conclude that providing "an easily accessible collection of gathered data" will help designers remain focused on user needs. Clear communication of needs and requirements to designers in a way that is meaningful and relevant is therefore a crucial component of UCD.

UCD methodologies are often based on the international standard BS EN ISO 9241-210: 2010 which provides principles for involving users in design but does not prescribe the methods. Four main activities are recommended within an iterative development cycle:

- Understanding and specifying the context of use.
- Specifying the user requirements.

- Producing design solutions.

- Evaluating the design.

The theoretical framework underpinning any UCD methodology will shape how data are collected and analysed; how problems are framed (Dorst and Cross, 2001) and ultimately the nature of design outcomes. UCD methods and approaches have over time been informed by many different disciplines including sociology, economics, and psychology (Pettersen and Boks, 2008).

Informed by sociological theory, practice-orientated approaches prioritise understanding of routines, habits, conventions and conceptions of normality over efforts to make individual technologies or behaviours more efficient (Shove, 2003). It is argued that practice theory provides a meaningful theoretical framework for considering issues relating to consumption (including purchase and use) and for dealing with less tangible issues relating to user acceptance and unpredicted changes in user behaviour that might result from design interventions (Scott, *et al*, 2009). A focus on practice also provides insight into how new technologies and products are normalized into domestic life leading to new practices and social norms (Shove and Southerton, 2000).

The core argument of practice theory is that the things people actually do should be central to the understanding of social phenomena. Practice theory has been described as a somewhat "fragmented body of theories" (Gram-Hanssen 2010), with varying significance being assigned to the role of material 'things' and technologies. Some theorists, for example Schatzki (1996), consider technologies to be the result of social practices. In contrast, the socio-technical perspective describes how technologies and 'things' play an integral role in shaping the evolution of practices (Shove and Warde, 2002; Shove and Pantzar, 2005; Gram-Hanssen, 2010). Significantly in the context of reducing domestic energy demand, the socio-technical perspective emphasises how our patterns of consumption are not just a matter of choice but are significantly shaped by the socio-material systems within which we operate, including the service infrastructure that delivers energy to the home; the layout of our homes; their material structure and technologies we acquire and use within them (Shove and Warde, 2002, Gram-Hanssen, 2010). Therefore significant one-off acts of consumption

(such as the installation of a new heating system) will affect domestic practice and energy consumption for years to come and so understanding the reasons for these occasional practices can be considered an important part of domestic energy use research.

Common ground between UCD and practice theory naturally exist. Understanding the context of use is a core premise of UCD (BS EN ISO 9241-210, 2010) and practice theory and, in particular, socio-technical perspectives can potentially provide rich insights into how products and technologies shape and are shaped by the contexts in which they are used (Ingram, *et al.*, 2007). UCD also has a long history relating to the design of socio-technical systems (e.g. Eason, 1988, Mumford, 2000), but typically in relation to the design of complex organisational systems rather than in a domestic context.

Within Sustainable Design, UCD methodologies based on psychological approaches that predominately focus on understanding attitudes, values and motivations (e.g. Stern, 2000) are more prevalent than their sociological counterparts. For example, Design for Sustainable Behaviour is a UCD approach grounded in behavioural theory (Lilley, *et al.*, 2005). However, within other fields, most notably Human Computer Interaction (HCI), UCD approaches based on sociological theory are more established (e.g. Taylor and Harper, 2003; Berg, *et al.*, 2003). Shove advocates a greater application of practice theory within Sustainable Design as there is the opportunity through the design of products to purposefully influence practices in order to reduce energy consumption (Shove 2003). However, despite the meaningful contributions of practice theory to the understanding of domestic energy consumption, the connections between practice theory and design are as yet underdeveloped (Ingram, *et al.*, 2007; Kuijer and de Jong 2009). Where links have been established these have focussed predominately on the early conceptual stages of product design (Kuijer and de Jong 2009; Scott, *et al.*, 2009) rather than on the design of the specific energy efficiency technologies that are the focus of the CALEBRE project.

Within the context of the CALEBRE project a practice-orientated UCD approach provided the opportunity to:
- Understand existing home improvement practices.

- Understand how the energy saving measures proposed may impact upon existing everyday practices.

- Consider not only the use but also purchase of energy efficiency measures by householders.

- Ensure that knowledge of everyday practices informed product development by the technologists and engineers.

- Ensure a systemic approach to considering user needs (as opposed to considering the design of each technology in isolation).

Additionally, focusing on practices within the home had other methodological benefits. Many of the technologies under development were likely to be considered novel or complex by householders. By concentrating on practices, householders would be able to narrate stories about their homes and way of life. They should, with the help of appropriate questioning, be able to comment on how a technology might fit into their everyday lives without knowing the detail of how the technology worked. It was anticipated that the researchers would then be able to interpret practices to identify implications for design of the retrofit process and inform the engineering-driven product development.

3 Methodological challenges within the project

Previous practice-orientated approaches within UCD have focussed on the early creative stages of consumer product design where opportunities for innovation are identified (e.g. Berg, *et al.*, 2003; Kuijer and de Jong, 2009). The CALEBRE project focus was on the development of existing concepts, and in some cases early prototypes, of energy saving measures by technologists and engineers rather than industrial designers operating within a creative concept design process. This led to the particular methodological challenges outlined in the sections below:

3.1 A range of technologies were being designed

A range of energy efficiency measures are being developed within CALEBRE: efficient energy supply through retrofittable heat pumps (gas and electric), energy management and control (mechanical ventilation heat recovery (MVHR) systems) and advanced insulation (vacuum

glazing and advanced surface treatments for moisture and temperature control). Generating user requirements to inform such a wide range of technologies placed a strain upon the user research as an equally wide range of daily practices needed to be considered. This made direct participant observation impractical and also meant that the research would need to provide a broad overview of relevant everyday practices rather than detailed exploration of one practice or daily routine.

The CALEBRE project team recognised that although each technology is being developed separately, each house is likely to require a suite of energy efficiency measures. The most appropriate solution for each house will vary according to the physical characteristics of the house but may also be shaped by the practices and preferences of the household. The researchers, whilst recognising that they needed to provide user requirements for each technology, wanted an approach that also allowed them to take a more systemic view that took into account the potential interplay between the different technologies within a future retrofitting context. A practice-orientated approach facilitates this but again the wide range of practices of potential relevance was problematic given that the study needed to be kept to a length that was acceptable to householders and achievable within the timescales of the project.

3.2   The findings must be meaningful and relevant to technologists

Development of each of the energy efficient measures is engineering-driven, being led by experts in their respective fields with their main focus on technical performance. The context for practice-orientated research is more usually a design team comprising of researchers, product or industrial designers and perhaps the users themselves (Scott, *et al.*, 2009), where there is a focus upon conceptualizing user needs in a way that enables designers to iteratively formulate design problems and begin to explore solutions (Dorst and Cross 2001). Engineering design is typically a much more structured process involving the creation of design specification documents. In keeping with the principles of UCD, it was essential that the outcomes of the user research could be conveyed to the project technologists in a meaningful and familiar form (Preece, *et al.*, 2002).

3.3   The technologists required specific user requirements

Practice-orientated research is often focused upon supporting product innovation and the identification of unmet user needs. CALEBRE is developing advanced technology-based interventions to increase the energy efficiency of older properties. Through dialogue with the technology developers, the researchers realised that the technologists had some very specific questions that they wanted answering in order to tailor technology development to meet user requirements. For example, heat pump-based heating systems provide constant background heat to the home but radiators are likely to operate at a lower temperature than the householders are currently accustomed to. The technologists wanted to know whether the practice of drying clothes on radiators was commonplace in order to assess whether cooler radiators would be acceptable to householders. Therefore, rather than enabling an understanding of everyday practices to drive design and present opportunities for innovation, the study was on the whole seeking to target particular practices in order to address specific technology related questions.

As well as encouraging the product technologists to provide specific questions to inform the user research, the researchers also spent considerable time developing a detailed understanding of each of the technologies under development in order to predict the likely impact of existing practices upon the efficiency of the proposed interventions. This again created the need for targeted investigation of particular practices rather than the creation of a practice driven innovation process.

3.4   Uncovering motivations for making home improvements

Although the householders were aware that the study was about making 'hard to treat' homes more energy efficient, the researchers wanting to uncover the householders' motivations for making any type of home improvement so that future policies developed to support retrofitting reflected the aspirations of householders regarding the upkeep and improvement of their property. The researchers were also interested in exploring whether saving energy was already a driver for making changes to the property or whether other factors were of greater importance to householders. The methodology was therefore designed so that attitudes to energy saving and climate change were not discussed directly until the second of two visits, allowing initial discussions to centre upon home improvement

practices, enabling motivations for making changes to the property to be explored freely without potentially biasing the findings through directly questioning participants about their energy saving practices.

3.5   Significant one-off acts of consumption

Practice-orientated research usually focuses upon everyday practices such as bathing (Scott, *et al.*, 2009) or doing the laundry (Pink 2005). Such practices may not literally occur every day but are routine aspects of a household's day to day existence. The introduction of energy efficiency measures within the home requires the home owner to make one-off, often expensive and perhaps irreversible purchase decisions that will constrain and shape consumption for years to come. The researchers therefore wished to investigate existing home improvement practices to understand how these are embedded in the everyday lives of householders and how they relate to life events and the lifecycle of the home.

Home improvements increase the value of a property as opposed to maintenance activities that are aimed at offsetting physical deterioration (Potepan 1987). Reschovsky (1992) reports that home improvement is one of the least studied aspects of housing economics and to date little is known about home improvement practices or how they impact upon the retrofitting of energy efficiency measures. Studying these practices required the development of a method to support recollection of past actions and decision making processes. Previous research has shown that visual representations of context considerably help participants recall past events and make associations between them (Kensing, 1998, Smith, *et al.* 2002, Mitchell, *et al.*, 2004). Storytelling has also been identified as a valuable medium for describing not only actions but also feelings and motivations (Erickson, 1996) and is frequently used within many user centred and particularly Participatory Design approaches to encourage users to provide rich contextual detail about their everyday lives (Muller, 2003).

4 Research tools

The challenges described above led to the development of a practice-orientated UCD approach supplemented with more traditional UCD activities and were also used as a

framework to evaluate the success of the approach taken. The approach focused on the first two activities from BS EN ISO 9241-210: Understanding and specifying the context of use and Specifying the user requirements. Two main components of the adopted approach are described in this paper: the timeline tool developed to explore home improvement practices (the context of use) and the development of product requirement trees for each technology to structure the data collected (specification of user requirements).

4.1 The timeline tool

To encourage householders to share their stories and engage with the research process, a timeline tool was developed to prompt recollection of past home improvements and other life events that had taken place since the participants had purchased their house. Development of the tool built on previous work by Haines, *et al.* (2006) and Kanstrup and Christiansen (2006), where an engaging data collection approach was required that respected the privacy of the householders and encouraged individuals to take part in the study during their leisure orientated time at home. The timeline tool set out to achieve the following objectives:

- To gather data about home improvement practices since the participants had moved into their home.
- To engender storytelling about participants' experiences, so that motivations and barriers underlying the practices could be explored as part of an enjoyable activity.
- To allow analysis of the data in a structured format (e.g. chronological order of home improvements) even if data were presented randomly.

To ensure a relaxed atmosphere but in a space where participants were happy to meet with the researchers, interviews were conducted in a room of the participants' choice, often around a dining table.

The development of the timeline allowed participants a degree of control over the data collection process, a methodological requirement raised by others including Crabtree and Rodden (2004) and Kanstrup and Christiansen (2006). Participants were asked about their home from the point of purchase, exploring issues relating to why they chose the particular property, whether they moved in straight away and if they undertook any home improvements at this stage. This established a known starting point which was generally

easily recalled by participants. Participants were then asked about other improvements they had made to their home, for example major renovation, replacement of heating systems, wiring, structural changes etc.

As participants volunteered information, the timeline was drawn up in front of them, using pen on magnetic boards, supported by a bespoke set of magnetic cards containing relevant images which could be added to the timeline to indicate particular aspects. These were in several categories: dates (to structure the timeline), life events (birth of a child, wedding, etc) and home improvements (double glazing, new boiler etc). These were added when the participant mentioned a particular activity or event, and notes added along the timeline to provide a pictorial and text based record. Mateas, *et al*. (1996) used a similar approach with felt pieces and a flannel board to assist householders to walk through their day. They comment that the visual and tactile engagement of the board facilitated recall and kept the conversation grounded.

Participants were also prompted for information about disruption relating to each event, and approximate time and cost of the activity. Where professional tradespeople had carried out the work, participants were asked about how and why they chose the particular supplier and whether they had carried out any of the work themselves, in order to inform the researchers about the process of home improvement. Figure 1 shows a timeline in development and Figure 2 shows an example of the completed item.

Figure 1. Timeline in development
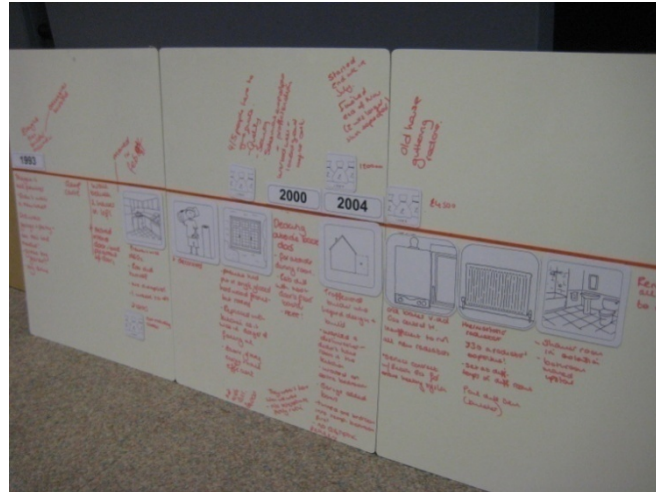
Figure 2. Completed timeline

As participants were able to see the development of the timeline, they were fully aware of the type of data being recorded. They were also free to volunteer information as they wished, in any order they chose, as a formalised set of questions was not presented.

4.2 Requirement trees

Requirement trees were identified as an appropriate communication tool for translating insights from the user research into user requirements presented in a form familiar to the engineers. Requirement trees aim to convert non technical, non-quantified customer requirements into a set of product characteristics (Wright, 1998), and so could be used to organise the range of requirements from householders into something that was useable by the technologists. These could then be developed into product design specifications, which form a conclusion to the first stage of a typical engineering design process. Roy's model of the design process (1996) identifies four key phases to an engineering-orientated product development process: Task Clarification; Conceptual Design; Embodiment Design and Detail design. The requirement trees and design specification are generated as a result of the Task Clarification process, following the development of ideas, needs and an initial brief.

The requirement trees took a user perspective and were based on the whole lifecycle of a technology from 'decision to purchase' to 'end of life'. This allowed for a very structured, systematic approach to considering how a product might be purchased, transported to the property (by a home owner or professional), installed, used, maintained, decommissioned

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and disposed of at the end of its life. For each of these aspects of the life cycle, issues that would affect the user were listed. These were then expanded further to ensure the full details of the requirements were considered. This was done using expert opinion (based on human factors knowledge and reviewed literature about each technology, as well as discussions with the respective technologists), which populated these requirement trees as far as possible. Quantifications were included wherever available, for example no thicker than x cm, expected life span of y years. Thus, the trees included issues relating to the design of the products as well as the process of installation. There were a number of areas where it was not possible to determine or quantify requirements from expert knowledge or the literature and these needed first-hand evidence to inform the design process; these gaps defined the interview areas and, in some cases, the specific questions that needed to be asked. An interview structure and detailed questions were designed around understanding practices within the home that would inform the technology design. For example, door closing practices will influence the effectiveness of a retrofitted centralised mechanical ventilation system. If it was found that people habitually closed all internal doors, then a single duct ventilation system is unlikely to be successful as there would be insufficient airflow around the house, and so the design of the ventilation technology would have to include multiple entry / exit points or some other workaround.

5 Study outline

Given the range and type of data required, the data collection was conducted over two visits; the first visit was to establish a rapport with the householders and understand their home improvement practices since moving into their home. The second visit focussed more specifically on the energy efficient technologies being developed within the project and sought to elicit knowledge relating to how these might fit into people's homes, lifestyles and everyday practices. Data in visit 1 were collected through an in-depth semi-structured interview and the use of the timeline tool. Visit 2 similarly used an in-depth semi-structured interview approach, but also presented participants with factsheets about the technologies, and included a tour of the home in order to take photographs of relevant features mentioned in the two interviews and to better understand the material structure of the home. This second interview also investigated the participants' attitudes towards climate

change and energy saving;; their first impressions of the specific energy saving technologies; daily practices related to these technologies (e.g. whether participants habitually open bedroom windows at night) and the factors influencing the participants' willingness to adopt each of the specific technologies (e.g. cost, payback times, aesthetics, comfort); the structure and layout of the house and how it impacted upon use of different spaces within the house. The home tour was scheduled for the second visit to allow trust to be established between the participants and the researchers during the first visit (Dray and Mrazek 1996, Kanstrup, and Christiansen 2006).

Following agreement to take part in the study, householders were visited at their homes at pre-arranged times, often in the evening when all adults could participate. Two researchers attended each visit, for ethical reasons and to provide a lead interviewer who could focus on the discussion and a note taker who could ensure all details were recorded. Discussions were also recorded with a digital Dictaphone and later transcribed in full.

A total of twenty households from the East Midlands area of the UK were selected to take part in the research. These twenty households (which included a total of 66 permanent occupants) were recruited using a variety of methods: advertising, word of mouth and direct approach and were selected to represent a wide range of owner occupied, solid-walled houses. This allowed for a range of house and household types to be selected for the study, representing a range of family structures, incomes and social status to provide a spread of participants. Whilst this was never intended to be a statistically representative sample, it allowed for a snapshot of different domestic situations to be explored in detail.

6 Results

The wealth of timeline information and supporting qualitative data were analysed to identify key home improvement practices and those that related to the CALEBRE technologies (heating system, glazing, ventilation, insulation) were focused on in detail. This paper only reports information relating to the home improvement practices of replacing or repairing windows, as an illustrative example of an energy saving technology and to provide a focus for reflection on the methodology.

Participants readily provided information about their lives and activities around their home. The timeline context helped recall of events that happened sometimes over a decade ago. Wherever possible the researchers had asked for all adults in the family to take part in the interviews and in particular in the construction of the timeline. This considerably enriched the storytelling experience as the couples involved helped each other remember the context and details of specific home improvements as each was added to the timeline. Participants reminisced over events and incidents associated with making these changes (e.g. recalling with affection Do-It-Yourself (DIY) disasters which at the time were less amusing and how the family coped whilst their everyday lives were disrupted by building work). This interplay also revealed many insights into the dynamics of the home improvement decision making process, for example how couples made decisions about what changes to make to the home and how improvements could stall altogether when the couples were unable to agree. Interviews with householders using the timeline were anticipated to last approximately one hour. However, it was commonplace for interviews to extend over two hours because participants were so engaged in the process and enjoying retelling stories of their lives in their homes. It was not unusual for householders to want to go back over material already covered, to provide more information, or discuss events in a greater level of detail than was required for the study. When returning for the second interviews, several participants added information relating to the first visit, or provided other unprompted recollections.

Participants in eighteen of the twenty houses had undertaken some home improvements relating to their windows, including replacing all or most of their windows with new, replacing only some of the windows, repairing windows and repainting or refurbishing windows. Each household's individual story relating to when, why and how they had improved their windows was collected as part of the timeline activity in visit one. Current window opening practices were then explored in more detail in visit two. The tour of the home conducted as part of the second visit also provided additional information about the participants' aesthetic and comfort preferences and the structural idiosyncrasies of the particular property. Table 1 details findings relating to three window design issues to demonstrate how the comments from the householders were translated into requirements for the requirement trees.

Table 1. Translation of householder comments into Requirements

Householder comments	Implications	Requirement
Issue: Windows in keeping with the original character of the property		
H3 *"There's one window that we haven't replaced because they can't do it in a nice way that's sympathetic to the style…"* H9 *"this one is styled the same with the narrow side pieces and the transom so it started like the original Victorian windows…and again with the upper ones, we had them to look like they were sash windows."* H10 *"They are double glazed sash wooden timber windows...We're in a conservation area and also I thought if you're going to do it, you might as well do it well."* H12 *"..they kept saying, do you want double glazed windows, and we said 'no because it spoils the house"* H12 *"modern glass is like a float glass, it's perfectly flat, but this is like drawn, so it's got a slight ripple in it…we had some cracked glass so they replaced them with the drawn glass, so it's all done in keeping"* H13 *"because we didn't want to spoil the look of the window…the primary window"* H18 *"so we still had the original bay window and the original sash window at the top...we were worried...we would lose the feel of the house, because this bay window was a lovely thing."*	Many householders want wooden window frames and this issues is more important to householders than energy saving performance or glazing type. Some householders want new glass to include visible imperfections to give the appearance of old. Conservation areas require new windows to maintain appearance of old.	Window frames need to be available in range of materials, including wood. Windows must be available in all styles to match existing windows in older properties. Appearance of the glass (including coatings & reflective properties) needs to be similar to original windows. Windows need to function effectively in all configurations including with sash mechanisms.
Issue: Windows allow easy on-going maintenance		
H12 *"…they've got like little plastic fasteners, so you unclip them...then you can just take both sashes out, top and bottom...it does mean you can take them out and paint them properly."* H18 *"(they are) on a hinge system so it*	On-going maintenance must be possible; design must allow window components to be dismantled easily for repainting / refurbishment.	Windows need to withstand routine removal and replacement during their lifespan.

makes it easier to decorate. So you could unhook the rope on the sash and then hook them on to a small hinge and then ease them out so you can paint"		
Issue: Possible to replace only part of a window		
H8 *"we did have a window [pane] replaced because somebody threw something through it"* H10 *"At the front, there was some more weathering on the bottom of the wood and he had to replace some bits of wood."*	Wear or damage may require a partial replacement; for reasons of cost and convenience, this must be possible.	Windows need to be available as individual components without compromising overall performance. Window frames must be repairable without compromising performance of vacuum sealed sections.

The requirement trees were drawn using Microsoft Visio and developed into large documents, too large to be reproduced in this paper. An extract from the "Consumer Appealing Windows" requirement tree is shown in Figure 3.
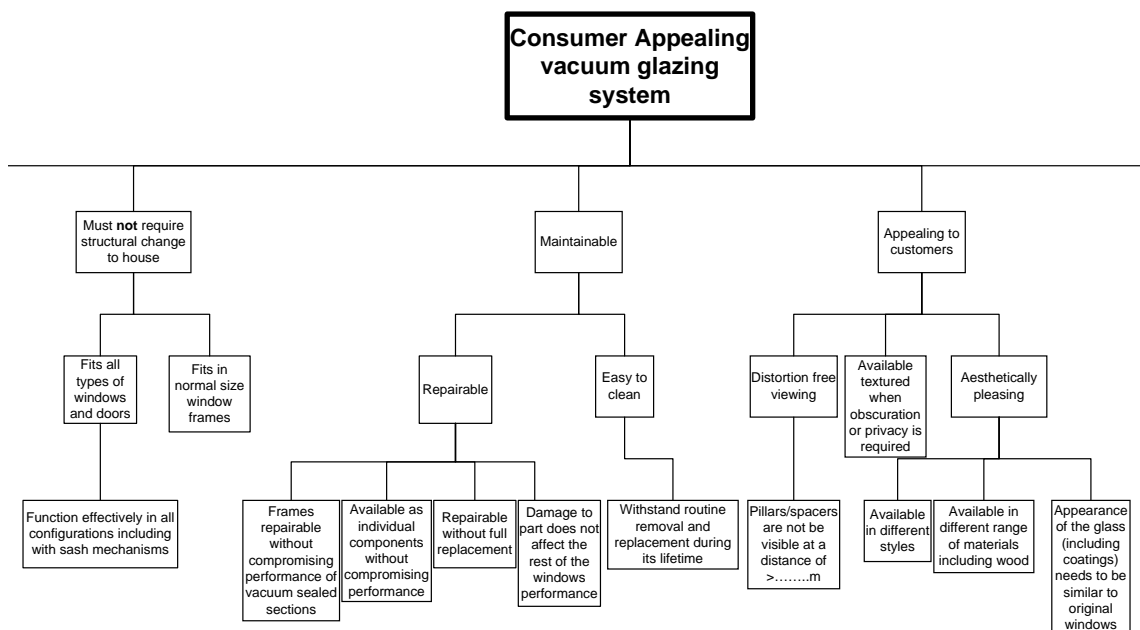
Figure 3. Detailed extract from the "Consumer Appealing Windows" Requirement Tree

7 Meeting the challenges

This study aimed to identify whether an understanding of home improvement practices could be translated into a form suitable for use by technologists within the context of the CALEBRE project and a range of challenges were identified. This section describes the degree to which the approach taken met the challenges set.

7.1 A range of technologies were being designed

By looking at practices, this research has considered home improvements in a systemic manner although the energy saving technologies within the CALEBRE project are being developed in isolation (by specialists in each field). The translation of participants comments into requirements allowed for the holistic comments to be separated out into requirement trees for each technology, ensuring only relevant information was passed on to each technologist. However, staged development of the requirement trees did require specific questions to be asked about daily practices for each of the energy saving measures under development within the project. This required each technology to be introduced separately to the homeowners and then a series of practice-orientated questions asked that raised issues pertinent to the design and implementation of that particular technology. In contrast to the discussions centred around the timeline, the resulting discussion of everyday practices, carried out in the second interview, was somewhat disjointed and less rich in contextual detail. However a good deal of useful information that was needed to inform the requirement trees was elicited through this process.

7.2 The findings must be meaningful and relevant to technologists

The glazing example provided in the results section shows how the comments from householders were translated into a format that engineers could use within their technology development processes. Through the provision of requirements in a form familiar to them, the technologists in the project were able to understand how the collection of qualitative data could inform the design of their products within the context of their engineering driven product development process. This was illustrated by one project partner who commented "*interacting with you at this early stage of development of our technologies is a good thing....From my experience in design and manufacturing, there is a*

tendency for technologists to completely ignore what the consumer thinks and just focus on the products". The timeline data have been highly valued by the engineers within the project seeking to understand how the order in which the retrofitting of energy saving technologies takes place impacts upon the energy efficiency of a house. For example, the timeline data showed that central heating systems are often changed soon after a family move into an older property and windows may be improved in a piecemeal fashion or not at all, in order to keep the character of an older house. From an engineering perspective, a more energy efficient house is achieved when the boiler is changed after windows are upgraded and the house is made more air tight. This knowledge of how actual home improvement practices differs from optimal practice has highlighted the need for further research into the order of retrofit and how predictive modelling of the savings to be made needs to be based on better understanding of people's actual home improvement practices.

7.3 The technologists required specific user requirements

The researchers were acutely aware of the tension caused by needing to gather specific user requirements for a diverse range of technologies whilst still seeking to understand how the design of these technologies could be refined through understanding of everyday practices and routines. Analysis of the data from both visits allowed the comments made by participants to be collated and translated into implications and then requirements, as shown in the glazing example in this paper. By structuring aspects of the data collection around the requirement trees, it was also possible to identify questions that would specifically address the needs of the technologists.

Data collection focussed more than the researchers had hoped upon the impact of individual technologies. Whereas they had intended to develop a more holistic approach that reflected the likely implementation scenario where each 'hard to treat' property is treated with a range of customised suite of energy efficiency measures, the sheer volume of issues to be considered led to a more piecemeal approach being adopted. Further research will seek to focus upon daily routines (for example coming home from work or putting the children to bed) which will allow the interplay between daily practices and systemic implementation of energy saving measures to be more fully explored.

Because of the parallel nature of the workpackages within the CALEBRE project, the technologies were being developed at the same time as the user requirements capture. Although a traditional design process might require exploration of a problem before generation of solutions (e.g. Cross, 2008 p30) it is increasingly acknowledged that the design process can take a less firm route such that Evaluation, Analysis and Synthesis are linked in an iterative cycle (Lawson, 2005, p40). Whilst the various CALEBRE technology prototypes are being developed largely independently to the data collection of this study, the findings will inform evaluation strategies of these prototypes and will specify the requirements for subsequent generation products. For example, having been shown the relevant requirement tree, one project technologist commented "*as a result of our meeting today, we'll expand our test regime*." This suggests that although the reported research focused on the first two activities described in the BS EN ISO 9241-210 standard, it may be fruitful to expand the existing practice-orientated UCD approach to encompass the production and evaluation of design solutions.

7.4   Uncovering motivations for making home improvements

Participants rarely mentioned energy as a motivator for making home improvements (despite knowing the data collection was for an energy related project); instead issues relating to improved living conditions, reduced cost and more pleasant surroundings were cited as motivating factors for making significant changes to their homes. The study led to abundant data about home improvement practices and supporting information about everyday practices of relevance to the development of the project technologies. Participants were able to recall numerous home improvements undertaken in their homes, building up detail as each event was explored in discussion. By splitting the data collection into two visits, trust was built between the researchers and the participants and participants were able to openly recall their lives in their homes and reflect on the achievements (and sometimes failures!) of their many home improvements. Data collection from the two visits sometimes overlapped, for example visit one included discussion of past home improvement practices relating to replacing windows as part of the timeline activity and in visit two windows were again discussed as part of the discussion of the participants' willingness to adopt the proposed technologies and again as part of the home tour. This

enabled some triangulation of data to take place and extremely few inconsistencies were found between the participant's responses across the three data collection activities.

7.5   Significant one-off acts of consumption

The timeline tool provided a flexible structure for storytelling that helped the participants recall significant home improvement practices in relation to life events (e.g. a child leaving for university). Although participants sometimes struggled to remember exactly when improvements were made (and in such circumstances were reassured by the researcher that exact dates were not needed), they were usually able to identify the sequence in which home improvements took place through discussion around the timeline, and were able to recall information about the motivations and triggers for making the improvements (for example, receiving a small inheritance or making an insurance claim). They were able to easily relate activities to life events, often using these as a starting point for the discussion: "*it was just after our son was born…*". Because the timeline was constructed using magnetic cards and whiteboards, the timeline could be easily re-ordered when participants remembered an event out of sequence. This helped the researchers maintain a relaxed and informal dialogue with the participants, whilst still collecting structured and detailed data on home improvement practices. The combination of the two visits, with the first focusing on the significant one-off acts of consumption and the second addressing everyday practices, enabled a multi-faceted view of home improvement and its effects to be constructed.

7.6   General reflections

UCD practitioners are, at heart, problem solvers rather than theory builders. The diversity of theories that have, over the years, informed UCD approaches confirms the "practical before theoretical" stance of the discipline. Rather than developing or challenging practice theory, this study sought to frame exploration of the problem space using a socio-technical perspective. This allowed an exploration of the interplay between the material structure of the house and home improvement practices (Gram-Hanssen, 2010). Consideration of the relationship between consumption and the evolution of practice (e.g. Shove & Pantzer, 2005) led to a reflection of home improvements as practices that are embedded in the socio-economic and socio–material structures of the home. However, the rich insights on home improvement practices do have the potential to inform practice theory although this is

beyond the scope of this paper. For example, Gram-Hanssen (2010) describes how the material elements of practices associated with regulating the indoor climate of the home include the architectural layout of the house. The study data contained several examples of the re-purposing of loft space from storage to living space which provide further evidence of the re-interpretation of space and the co-evolution of practice.

The development of this bespoke methodological approach to meet specific project needs has led the researchers to reflect on their role within design and how it may evolve in the future. Current trends in design research show changing roles for both researchers and designers particularly when addressing 'wicked' open ended problems (Rittel and Webber, 1984) such as those arising from the urgent need to halt climate change and reduce the production of CO2 emissions. Sanders and Stappers (2008) describe what they term as a 'caricature' of the classical UCD process where the user is the passive object of study and the researcher contributes theoretical knowledge and further knowledge developed through observation and interviews. The designer then passively receives this knowledge in the form of a report and interprets it in relation to his understanding of technological and other constraints into design concepts, ideas etc. The role of the researcher in such a process is one of 'translator' between users and designers, gathering information about the context of use, then translating that information into requirements. They contrast this with the role of researchers within a Co-design process, where users are more actively engaged in the design process as 'experts of their own experience' and designers explore the design space collaboratively with users. In this context the role of the researcher is that of 'facilitator', providing tools and methods to enhance the contribution that users can directly make to design. Within practice-orientated research with its current emphasis on the early conceptual stages of the design process, the trend is also towards more direct contact between designers and users as designers seek to embrace the concept that interventions can lead to innovations in practice that then foster further opportunity for product innovation (Scott, *et al.*, 2009).

This study illustrates that there is a valid role within more technology-driven design processes for the researcher to still act as 'translator' between technologists and users providing a much needed bridge between the two. In order to address the design challenges

introduced in this paper the researchers have needed to invest considerable effort in firstly understanding the technologies under development, assessing how these may impact upon everyday and occasional practices and presenting these to users in an understandable and engaging form. The results of the user research then needed to be translated into a meaningful form suitable for informing the engineering-driven technology development process. Direct contact between technologists (designers) and users in this context is hard to envisage. However, the success of the timeline tool as a method for engaging householders in a discussion centred upon home improvement practices suggests that householders could in the future play a more direct role in the development of retrofitting products, policies and incentive schemes.

8 Conclusion

The approach outlined in this paper illustrates the development of a practice-orientated UCD approach developed in response to the particular needs of an engineering-driven development process. It was developed to address methodological challenges that arose from the need to provide user requirements to technologists in a meaningful and relevant form whilst still seeking to explore how everyday practices may influence the performance of the energy efficiency measures being developed within the project. As a successful retrofit process is dependent on consumers choosing to purchase and install available energy efficiency measures, the researchers also sought to understand existing home improvement practices so that the impact of future retrofitting policies can be maximized by understanding the triggers that lead to home owners undergoing home improvements and the motivations that lead them to make significant, often expensive, one-off changes to their homes.

The timeline tool was an effective and engaging tool for exploring existing home improvement practices. The conversion of the data from householders into requirement trees provided a structured and succinct approach to reporting the findings in a format that was familiar and useful to the technologists. The requirement trees have been well received by the technologists developing the energy efficiency measures and have enabled large

quantities of qualitative information to be represented in a way that is meaningful within the context of an engineering-driven product development process.

The research confirms that it is possible to use an understanding of home improvement practices to inform the design of energy saving measures in a domestic context. This confirms Shove's (2003) aspiration for greater application of practice theory within Sustainable Design. This paper has provided evidence that practice-orientated design approaches have real potential to improve the design of energy efficiency measures, which can ultimately lead to the reduction of domestic energy consumption.

Acknowledgements

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Haines, V.J.A. and Mitchell, V.A. (2014). A persona-based approach to domestic energy retrofit. Building Research & Information, Special Issue: Energy retrofits of owner-occupied homes, Volume 42, Issue 4, 462-476.

Abstract

In order to improve the efficiency of the housing stock successfully, the offered technical solutions also need to meet occupants' needs and match their aspirations. Owner-occupiers present particular challenges: conflicting demands on their use of time and financial resources and their role as decision-makers for their own domestic renovation. A persona-driven study (based on user-centred design) was undertaken to explore the varying behaviours, attitudes and motivations towards home improvement for owner-occupiers who live in 'hard to treat' solid-walled dwellings. Five evidence-based personas are constructed that reflect archetypes, based on the outcomes of a qualitative study involving 33 owner-occupier householders in the East Midlands region of the UK. The adoption of a persona-based approach in response to the socio-technical challenges of energy renovation is important for understanding the specific drivers and appropriate range of policy responses for each persona. The persona development process is described and the success of the approach is evaluated in relation to the needs of policy developers, energy providers and product developers. Tailoring strategies to suit different personas will considerably enhance the diffusion of policy goals for low-energy retrofit and also allow business and technology developers to target an appropriate user.

Keywords

Energy, homeowners, low carbon, motivation, personas, renovation, retrofit, user-centred design

Introduction

With 28% of the UK's energy used by the domestic sector (DECC, 2012) and at least 75% of the UK dwellings that will exist in 2050 already built (Wright, 2008) and a housing stock turnover of only about 1% per annum, there is a clear need for energy efficiency measures to focus on renovation of the existing stock. Whilst there are technical solutions that will minimise energy losses and reduce demand, these also need to meet people's needs and match their aspirations to be fully effective.

Owner-occupiers, who represent 65% of the UK housing stock (DECC, 2013), present particular challenges to policy-makers, designers and suppliers. As the decision-maker in the process, owner-occupiers face often conflicting demands upon their use of time and financial resources. In order to persuade this group to prioritise investment in energy renovation and domestic energy products and services, it is necessary to understand further their relationships to their homes and their attitudes towards making improvements to their homes. Hewitt (2012, p. 1) identifies that any technological intervention in addition to being cost-effective 'must be acceptable to the use, in terms of minimal disruption during installation, ease of use and alignment with lifestyle expectation'.

This paper reports the findings from a study of home improvement amongst a group of owner-occupiers in solid-wall dwellings (i.e. those built from brick or stone but with no air cavity between the layers of the external wall and so particularly hard to treat) and draws on tools from User Experience (UX) Design to help understand how these past home improvement projects can be used to describe different types of owner-occupiers in this context. As many home improvements include some aspect of energy efficiency (e.g. installing a new boiler and radiators, fitting draught-proofing or insulation), consideration of past home improvement activities provides a good proxy for prediction of future behaviour in terms of applying energy efficiency measures to the home. The aim was met though completion of the following objectives:

- A series of participative, semi-structured interviews were conducted with 33 owner occupier householders who resided within 20 hard to treat solid walled properties within the UK East Midlands region.
- A structured but creative data analysis process was used to construct a set of five personas that communicate archetypal behaviours, attitudes and motivations towards home improvement for the sample population.
- The potential usefulness of this persona set as a decision support tool was evaluated in relation to the needs of policy developers, energy providers and product developers.

Personas are archetypal users who embody the goals and aspirations of real users in an easy-to-assimilate and personable form. Personas were first developed as a tool to support the development of software (Cooper, 1999). Cooper (1999) recognised that software developers often had a poor understanding of the intended users for their products and would make design decisions based on unfounded assumptions about people's preferences and skills or would revert to making decisions based on people like themselves. He proposed the use of persona characters to improve team communications and to provide a consistent reference point for design activities. Personas are now used widely within many sectors of the design industry, particularly in relation to the design of user experiences for digital products and services (e.g. McKay, 2013; Mulder & Yaar, 2006). Personas can be assumption-based and such 'ad hoc' personas can be effective early in a project to articulate what is already known or being inferred about users (Adlin & Pruitt, 2010). However personas are generally accepted to be only as good as the data on which they are built and should therefore be based wherever possible on robust qualitative research (Cooper, 1999). The study presented in this paper attempts to provide this robust underpinning to the resulting personas in the context of domestic renovation.

Like Munro & Leather (2000), little distinction is made in this research between repair, maintenance and improvement, likewise the terms 'renovation' and 'refurbishment' are used interchangeably in this paper. Munro and Leather highlight the similarity between a repair project (e.g. where home owners replaced ill-fitting and draughty windows) and an improvement project (where replacement double-glazing had resulted in redecoration) indicating how these activities are inextricably linked. Retrofit refers more specifically to the installation of an energy-saving technology, retrofitted into an existing home (rather than being incorporated at the time of the build).

Home improvement

The literature reports that there are 15.5 million dwellings in England that are owner-occupied and 29% of these (4.5 million) have solid walls (DEFRA, 2008a). Solid-walled dwellings are located throughout the UK with 75% of the total solid-wall housing stock located in urban centres (not city centres) and suburban residential regions (Vadodaria,

Loveday, Haines, Mitchell, & Bayer, 2010). While 30% of the stock is in London and less than 3% is in the North East, the rest is located evenly in other regions of the UK. A total of 70% of the total solid-wall housing stock consists of end of terrace, mid-terrace, semi-detached and detached property types. Of particular relevance to this paper, 80% of the total solid-wall housing stock is owner-occupied and privately rented-occupied. Solid-wall dwellings have an even mix of household composition, which includes couples less than 60 years of age with and without dependent children, couples above the age of 60 years with no dependent children, multi-person household and lone parents, and as a whole have a mean SAP1 rating of 49.8 (Vadodaria *et al.*, 2010). As the least efficient sector of the housing stock, these hard-to-treat homes must be renovated to become more energy efficient. Whereas improvements to social housing can be undertaken at scale by a council or housing association, owner-occupiers have more freedom in renovating their homes (Baum & Hassan, 1999) and so improvements to the owner-occupied stock relies on individuals being motivated to initiate or complete the work. Earl & Peng (2011) identify motivations for undertaking home improvement activities to serve a particular purpose:

1. To enhance the market value of the property or its potential rental yield.
2. To increase the properties' marketability.
3. To enable the home owner to meet new or existing lifestyle aspirations more cheaply than by selling up and buying an alternative property.
4. To enable the homeowner to enjoy enhanced social standing.
5. To meet psychological goals via the process of achieving the improvement.

Given recent increases in fuel prices and incentives from government to reduce carbon emissions, an additional motivation might also be to reduce energy consumption. Gram-Hanssen (2014) reports other drivers for renovating dwellings, beyond cost and energy saving, including improving comfort, increasing indoor temperatures, maintaining against wear and tear, wanting a room or dwelling that is new and more fashionable, and even making a closer connection with the home, demonstrating the complexity of the topic. Gram-Hanssen categorises reasons for renovation relating to the result (product) of the renovation, lifestyle and project factors. Peng (2012) classifies reasons as functional needs

(similar to Gram-Hanssen's product), lifestyle pursuits (combining lifestyle and project) also mentioning investment as a factor.

Baum & Hassan (1999) use contextual factors to identify what affects people's motivation to renovate. They found that those households with higher incomes renovate more often and that larger households undertake more renovations than smaller ones. Phipps (1983) asserts that a lack of finances is interpreted to be the major underlying constraint facing households, but income was not found to be a significant variable for some of Baum and Hassan's participants. They did find that renovation tends to occur more often in older dwellings and that housing preferences and needs change throughout a household's life cycle.

Munro & Leather (2000) talk of 'consumption'-motivated expenditure ('nest building') on the home being prioritised over 'investment'-motivated work, which results in considerable disrepair within the owner-occupier stock. Although it might be expected that preservation of the heritage features of older homes would be a motivating factor for owner-occupiers (Earl & Peng, 2011), Hills & Worthing (2006) found that owners of character buildings invested in maintaining them only to avoid discomfort and costs of further deterioration and to get the satisfaction that went with keeping them in 'good order', rather than for cultural reasons. Munro & Leather (2000) identify five household lifecycle stages as being relevant to domestic repairs (young household; household with children; empty nester pre-retirement; older household; and household dissolution/death). They note that expenditure on the house often competed with other spending priorities, even in those households that were less cash-constrained. Williams (2008) reports that more affluent households are both more likely to outsource routine or mundane home improvement tasks and undertake a much larger number of tasks themselves, showing a complex link between income and home improvement activity. The decision to outsource renovation work is influenced by trust in contractors. Mallaband, Haines, & Mitchell (2013a, 2013b) report householders commissioning contractors who are not necessarily the most appropriate for a particular job, but are trusted, perhaps as a result of past experience or referral. Peng (2012) identifies a link between people lacking the desire to renovate their home and negative psychological attitudes towards renovation, which can include low trust in contractors. Peng (2013) also

identifies DIY-renovators as having lower trust in contractors when compared with those who commission a professional to undertake domestic renovation work.

Despite the diversity of the population and variety of motivations and barriers to home improvement (Energy Saving Trust,2011; Mallaband, Haines, & Mitchell, 2012), there has been little categorisation of types of home improvers. Baum & Hassan (1999) identify two groups of renovators from research in Adelaide, South Australia: Non-mover Renovators and Mover Renovators. Whilst not relating directly to energy improvements, this categorises people as those who are likely to stay in their homes and make improvements to them, and those who renovate with the primary motivation of selling their property and moving on. Munro & Leather (2000) refer to this group as Potential Movers who undertake works to improve the saleability of the property. With the economic downturn in recent years and the consequent stagnation in house prices, Non-mover Renovators may be becoming the dominant group with homeowners more likely to stay in their home and make improvements than move on to make a profit (Halifax, 2010).

Watson & Shove (2009) refer to a set of consumers outlined by one of their interview respondents, a design director of a major power tool manufacturer, which provides a limited typology of the do-it-yourself (DIY) market:

- "Confident Enthusiasts", having DIY experience and continued enthusiasm for DIY jobs at home;
- "Pragmatists", with experience and enthusiasm but finding little reward in doing DIY jobs at present;
- "Newbies" or "Assurance Seekers", who lack experience and confidence, but want to achieve a desired effect;
- "Hobbyists" or "Careful Perfectionists" , who do not necessarily have experience, but are driven by the pursuit of craft ideals and are concerned as much by the process as the final result.

This typology, albeit offered by one individual, focuses on the attributes of DIY experience, their confidence to carry out DIY and satisfaction gained from the process. Earl & Peng

(2011) also mention 'self-confidence' as a prerequisite for embarking on home improvements, reflecting the need for suitable capacity in a householder's life to take on a renovation project. This was also found by Mallaband *et al*. (2012), where householders need sufficient personal capacity before they can embark on a project. For some people, the idea of home improvement activities is challenging and a source of excitement, for others it causes anxiety (Earl & Peng, 2011). Earl and Peng also mention that householders procrastinate, rather than addressing repairs continuously, such that required repairs build up over time. They refer to a 'threshold of tolerance' that has to be reached before a householder will undertake some work on their property. This results in the piecemeal approach to renovation described by Fawcett (2013) and Fawcett & Mayne (2012) rather than a planned, whole-house approach that may be more cost and energy effective.

Williams (2008) identifies two kinds of consumers engaging in DIY: those who embrace it willingly and those who do so only reluctantly. These are further subdivided into those who are willing DIYers who want to improve the value of their home, who undertake DIY for pleasure and those who seek self-identity from the end product. Those who are reluctant can felt forced into DIY for economic reasons or have problems finding and using appropriate tradespeople.

Whilst these papers provide some categorisation of home improvement types within the population, past attempts to categorise the population within the energy demand reduction context have been limited. Archetypes are already commonly used in energy modelling to simplify the complexity of the housing stock, by adopting a number of dwelling archetypes which together represent the whole stock (Firth, Lomas, & Wright, 2010), but these relate only to the buildings and not the households who live within. DEFRA (2008b) classifies seven population segments based on people's willingness and ability to act pro-environmentally: Positive Greens; Waste Watchers; Concerned Consumers; Sideline Supporters; Cautious Participants; Stalled Starters; and Honestly Disengaged. Zhang, Siebers, & Aickelin (2012) highlight the limitations that this approach takes, as the effects of physical attributes of the home are ignored; the approach is also not at a household level. Zhang *et al*. (2012) propose eight archetypes of UK residential energy consumers based on three dimensions: energy efficiency level of the property, 'greenness' of the household's behaviour; and length of

daytime occupancy period: Pioneer Greens; Follower Greens; Concerned Greens, Home-stayers; Unconsciously Wasters; Regular Wasters; Daytime Wasters; and Disengaged Wasters. Whilst these relate to the household, they are not focused on home improvement activities and the potential for energy saving renovation.

In a report for the Joseph Rowntree Foundation into the market potential for smart homes (Pragnell, Spence, & Moore, 2000), three broad segments are identified: The Interested, The Ambivalent and The Uninterested. Whilst these are likely to cover the whole population, the lack of detail or focus provides little assistance to the designer or developer. More recently, market segments have been used by utility companies to target service or product propositions, but these remain commercially confidential and so do not aid the wider community.

The authors conclude from the literature that there is a lack of clear and targeted information that describe the range of existing householders within the context of domestic renovation, particularly owner-occupiers, to help guide designers and developers towards solutions that meet individual needs. Whilst it is impractical to provide bespoke solutions for the whole population, identification of needs for groups of similar individuals does provide a valuable approach and this paper offers a possible way forward through the use of personas.

A user-centred design approach to energy demand reduction

Policy measures are attempting to encourage and support individuals towards reducing their domestic energy demand, e.g. through the Green Deal in the UK; and scientific advances are progressing the technical measures available through, e.g. solid-wall insulation or improved heat pump design. However, the issues involved in reducing energy demand are complex and interrelated and so require a holistic or systems perspective in order to ensure they are successful. Rittel & Webber (1973) described these types of societal problems as 'wicked' problems; they are ill-defined, they have no clear 'stopping point', they may only achieve a 'good enough' endpoint, they are without a time span, and the solutions are intertwined with the problem. As domestic energy demand reduction is a wicked problem with complex socio-technical components, user-centred design (UCD) lends

itself well to offering a systemic approach, or suite of approaches. By focusing on the needs of the user and considering the range of activities undertaken in the context of the wider domestic environment, it is possible to consider the issue from a broader perspective.

UCD offers a process by which the user is considered central to the system and any design solutions (which could be products, services or systems); it provides a means to ensure the context of use and user needs are included within the design process, by considering physical, cognitive, social and cultural factors (Gould & Lewis, 1985). To achieve most success, users should be considered from the outset of a design process, as well as throughout, including continued consultation even after a product, service or system is in use. However, it can be difficult for designers and technology developers to identify users and research their needs, particularly when the market is diverse or ill-defined (Kujala & Kauppinen, 2004).

Within UCD, personas have emerged as a popular method to manage representation of users within the design process (Marshall *et al.*, 2013). Personas should not be confused with market segments. Market segmentation is used primarily to identify groups of consumers who will be receptive to a similar product, service or marketing campaign. Segments are usually defined by socio-demographic variables such as age, gender, income and location, although more sophisticated tools including psychographics (Wells, 1975) may also utilise analysis of psychological and behavioural variables such lifestyles, values and decision-making patterns. Typical psychographic variables include activities, needs, values and personality. Whereas market research techniques using these psychographic variables seek to provide a quantitative breakdown of the likely market, based on large representative sample sizes, personas encompass a similarly wide range of variables but utilise rich qualitative data from much smaller samples, with the primary purpose to aid design decision-making (Pruitt & Adlin, 2006). Cooper & Reimann (2003) acknowledge the pre-existence of psychographics, but market segmentation and personas should be viewed as complementary tools (Brechin, 2008).

Pruitt & Adlin (2006) highlight three particular benefits related to using personas. Firstly, personas make any assumptions being held by the design team explicit and therefore help

build a shared understanding of who is being designed for. Secondly, personas support decision-making by providing a small number of specific users to design for. Although focusing the design of a product or service to meet the needs of a narrow group of users can sound dangerously limiting, designing for a few well-defined personas provides meaningful constraints and boundaries to the problem space and therefore is likely to improve the quality of design decisions (Dorst & Cross, 2001). Finally, as personas contain personal and believable characteristics, they are more engaging than other representations of user data. A well-defined persona will therefore encourage empathy towards users and engage the interest of stakeholders.

However, not all are in favour of personas (Massanari, 2010). DeVoil (2010) questions the validity of using fictitious characters within design and advocates in line with Hackos & Redish (1998), the use of 'user profiles' that describe real rather than archetypal people. Rather than speculating how an imagined persona may react or behave, he argues that it is better to maintain an on-going dialogue with a real person, who may provide messy or inconvenient answers. Whereas any user-centred practitioner will support this view, it is not always practical or cost-effective to continuously or repeatedly engage users in the design process. This view also ignores the need to provide an evidence based description of user needs for a diverse range of stakeholders rather than a single design team. Personas are only as valid as the data on which they are built and a common criticism of the technique is that too many personas are not based on empirical evidence but assumption-based (Saffer, 2007); however, this criticism can be negated when personas are grounded in user research.

The personas within this research were primarily created to describe the archetypal approaches to home improvement that emerged with a view to understanding the barriers and opportunities to future eco-renovation. The developed set of home improvement personas represent the diversity of owner-occupiers with regards to the attitudes and motivations illustrated by the study population.

Methods

Data collection

Rich qualitative data were collected from a group of owner-occupiers who live in solid-walled dwellings. A study, which formed part of a larger research project on retrofit energy saving technologies for owner-occupiers (CALEBRE), was conducted with 20 households from the East Midlands area of the UK, with 33 participants contributing to the study, just exceeding the sample size of 30 suggested by Robson (2011) for single-group observations. The four-year CALEBRE research project aimed to establish a validated, comprehensive mechanism for reducing UK domestic carbon emissions within solid-walled housing that is acceptable and appealing to users. Although this project had a strong focus on energy, this study focused on the broader aspect of home improvement. Although the researchers were interested to see how home improvements might be linked to energy saving, this was not a key feature of the data collection, as its aim was to determine what other barriers and motivations existed.

The participants were selected to represent a wide range of dwelling and household types, representing a range of family structures, incomes and social statuses to provide a spread of participants. As it was never intended to be a statistically representative sample, this allowed for a snapshot of different domestic situations to be explored in detail and care was taken in the sample selection to ensure a broad spread of participants. Household characteristics considered included number of permanent occupants (mean = 3.3 people, range = 1–7 people), household income band (mean = £40 000–50 000, range = less than £10 000 to more than £80 000), number of permanent adult occupants (mean = 2.1 people, range = 1–5 people) and their ages (mean = 48.2 years, range = 18–80 years), number of children (mean = 1.1 children, range = 0–4 children) and their ages (mean = 6.9 years, range = less than 1 to 17 years), year of dwelling construction (mean = 1900, range = 1840–1930), location (city centre–rural), type of building (terrace–detached) and length of ownership (mean = 16.6 years, range = 3–35 years). Further details of the sample and its comparison with the UK stock are presented in Vadodaria, Loveday, & Haines (2014).

Interviews were conducted with all adult members of the household wherever possible using a semi-structured set of questions and a novel timeline tool, developed for the study (Haines, Mitchell, & Mallaband, 2012; Mallaband *et al*., 2013a). Participants were encouraged to use participative storytelling methods to capture, in rich detail, their past home improvement experiences, co-creating the timeline to develop a shared representation of the home improvements undertaken. From the interviews it was clear that renovation was not only an activity undertaken by the householders to improve their home, but also was a memorable emotive user experience, whereby satisfaction may be gained from learning new skills, completing a task or gaining a better home, replicating the complex accounts of home improvement activities reported to Munro & Leather (2000). It was apparent that members of a single household had different perspectives on, and attitudes towards, their home and renovation. These distinctions were captured within the conversations so they could be reflected in the resulting personas.

Development of the personas

Data collected in these interviews were used to create personas, developed using a process adopted from User Experience Design (Goodwin, 2010). Whereas personas are ideally developed to support the development of a particular product or service, the goal of this research was much broader. The home improvement personas were intended to support the needs of a wide range of policy and technology developers. The resulting personas were therefore designed to represent archetypal attitudes and motivations for making home improvements rather than to just support the design of particular product or policy. Data from the interviews were transcribed in full and then the following steps were followed to create the personas:

1. Behavioural and demographic variables were identified that were salient to understanding home improvement and also the energy demand reduction context. These variables emerged from a thematic analysis of the transcribed data, identifying a total of 26 variables that could be described in objective terms. These were expressed on a continuum, from low to high or as mutually exclusive variables. Variables included: Having a high or low motivation for DIY; Being a "moderniser" or a "restorer"; Having a high or low sensitivity to price; Having a high or low

concern about climate change; Liking a challenge or not liking a challenge; Having a high or low expectation of thermal comfort in the home.

2. Interviewees were mapped to the variables along each of these spectrums and in relation to each other, as shown in Figure 1. Based on their responses in the interviews, a tag representing each person was placed on each of the various scales by the researchers. Where there was uncertainty, evidence from the transcripts was identified to ensure appropriate placement.

3. The next stage was to identify and explain potential patterns in reference to the primary research. For example, two or more people who occur together on at least a third of the variables might be said to represent a pattern, but a meaningful reason for creating this pattern had to be apparent from the interview data. Transparent overlays were used to visually highlight groups of individuals where they sat together on a number of scales. Outliers were also of interest as they may be indicative of a separate persona.

4. Patterns were then clustered into skeleton personas, identifying particular common attributes of certain groups of people, again with frequent reference to the interview transcripts.

5. The next stage was to clarify distinctions and add detail to the skeleton persona characters by assigning characteristics from the data, such as demographic data, behaviours, frustrations, skills and attitudes. Some criteria which were important, but not critical, to defining the patterns were identified, for example gender, experience with technology. Goodwin (2010) recognises that these characteristics should be included within the persona set and so they were assigned in a way that enhanced the believability of each persona.

6. The final stage was to develop a narrative for each persona and to select realistic photos and quotes from the primary data in order to make the personas into believable characters.

Goodwin (2010) recommends that the number of final personas should be limited to between three and seven. From this research five evidence based personas emerged, two of which had subtypes, making seven in total.

**Figure 1. Mapping participants onto the variables**

The developed personas

An example persona developed from the data set presented in Figure 2 and Table 1 shows the full set without the graphical layout. This set represents archetypal owner-occupier families that live in solid-wall (hard to treat) UK homes. The primary purpose of the persona set is to inform the design of retrofit energy saving measures by providing insight into the everyday domestic contexts within which these measures will need to fit. In particular the personas represent:

- The attitudes and motivations of homeowners related to making improvements to their homes.
- Difficulties relating to making home improvements.
- How homeowners go about making these improvements.
- How these attitudes, motivations and behaviours result in opportunities and barriers to retrofit.

To aid quick visual comparison between the personas, some of the variables were summarised as a set scales on the persona sheet and the personas were allocated a point on the scale that best represented their type (Figure 2). These were initially based on the

patterns that had emerged from the research data. However these points on the scales were validated by the researchers independently assigning points on the scales. In most cases the researchers showed good agreement and the scale marker was fixed, however in one particular case there was less consistency. For 'Interest in energy saving' there was less agreement, as this was something that had not been explored directly in the home improvement orientated interviews. Householders had been asked about any problems that existed in their homes that related to being too hot or cold, damp and condensation, draughts or stuffiness, but not within the direct context of energy saving. For this scale, a decision was made based on the overall characteristics of the persona. For example, the Idealist Restorer (Figure 2) has a strong interest in energy saving as a construct of quality, reflecting an interest in clever technology, but only when this does not contradict with their primary goal of restoring the character of their property. As such, the Idealist Restorer has a relatively high interest in energy saving.
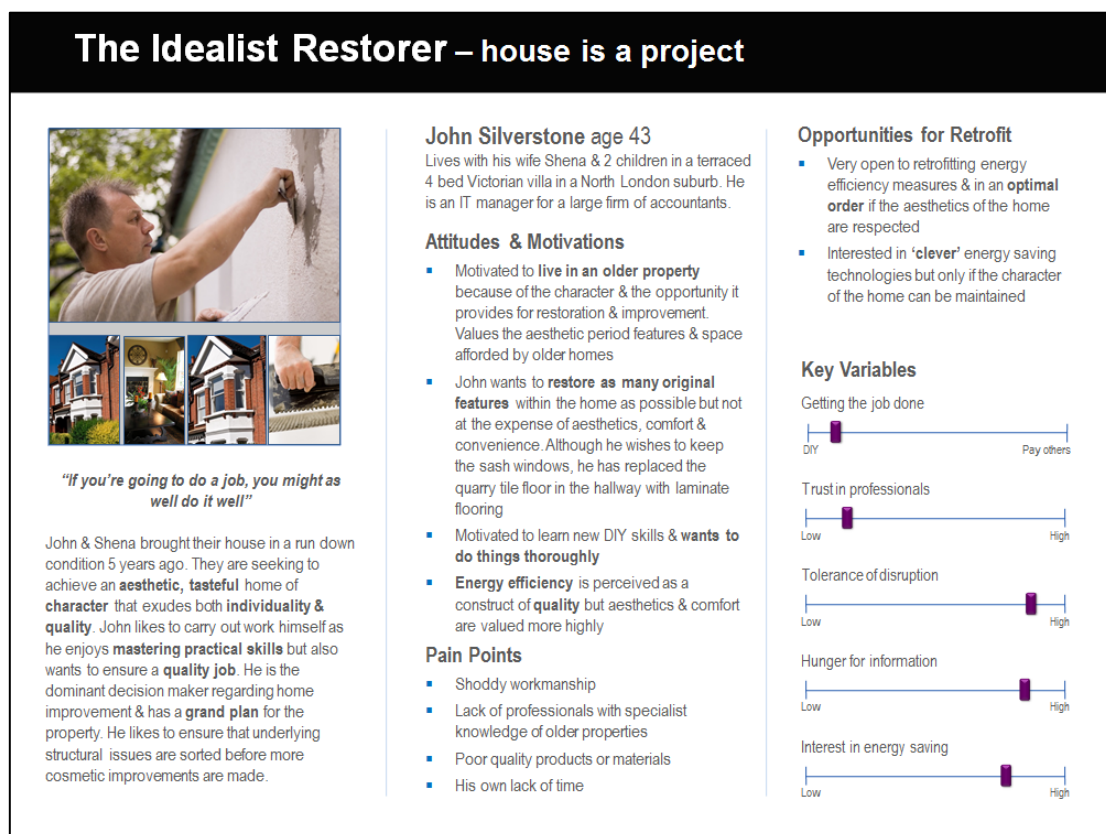
Figure 2. Example persona – the Idealist Restorer

Table 1. Key information from the set of home improvement personas

Persona (inc sub-type)	Key features	Opportunities for retrofit
The Idealist Restorer *The house is a project*	Motivated to live in an older property because of the character & the opportunity it provides for restoration & improvement. Values the aesthetic period features & space afforded by older homes Wants to restore as many original features within the home as possible but not at the expense of aesthetics, comfort & convenience. Although he wishes to keep the sash windows, he has replaced the quarry tile floor in the hallway with laminate flooring Motivated to learn new DIY skills & wants to do things thoroughly Energy efficiency is perceived as a construct of quality but aesthetics & comfort are valued more highly	Very open to retrofitting energy efficiency measures & in an optimal order if the aesthetics of the home are respected Interested in 'clever' energy saving technologies but only if the character of the home can be maintained
The Affluent Service Seeker *The house is a pleasure*	Motivated to live in an older property because of the character, idyllic rural location large garden & useful outbuildings. Accepts that older properties are expensive to maintain and views spending on the property as a way to preserve & add value to his investment Seeks luxury & quality but also value for money. Known to be financially savvy. Values comfort over financial saving Carries out very little DIY through choice but he is also less physically fit than when he was a younger man Energy efficiency is perceived as difficult to achieve in a large old property but Deniz is keen to take advantage of any grants or incentive schemes available.	Open to incentive schemes & polices that generate income for the homeowner or add value to the property Will choose to use specialist professionals to ensure a quality job
The Property Ladder Climber	Motivated to live in an older property by the potential it offers to add value to its resale	Open to the use of finance schemes if these

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The house is a step up	value through renovation Happy to borrow money in the short term to finance home improvements, paying these back when the house is sold Enjoy developing their DIY skills as the projects get bigger with each house they buy Open to consequential improvements as they are thinking at a whole house level but these improvements must lead to financial gain at the point of resale Energy saving beyond current building regulations is not a priority	are cost effective within the context of 'improving to sell' Unlikely to consider technologies with long payback times unless the cost of installation is passed on
The Pragmatist Sub-type: Functional *The house is a place to live*	Motivated to live in an older property because of the layout and room size that accommodates a full and active family life Home improvements are seen as a hassle rather than a hobby; they take time away from more important things - hobbies & family time Not particularly interested in keeping older features of the house, but place greater value on convenience Concerned about the environment and climate change, as a result of their family values	When things wear out or go wrong At the time of purchasing the house When re-purposing a space or extending the home When finance becomes available
The Pragmatist Sub-type: Aesthetic *The house is a home*	Motivated to live in an older property because of the character & space it offers Enjoy having a project on the go but improving or updating the decor, furniture & appliances within the home will be of higher priority than repurposing of space or non-essential maintenance Likely to cover up some issues like damp through frequent redecoration Values 'off the shelf' solutions, preferring to finance these from savings or windfalls rather than loans. Want a neat and tidy job to be done, with a good quality finish	When they first purchase the house or within the regular cycle of decorating and refurbishment The order of retrofit will be driven by aesthetic priorities, e.g. the desire for new kitchen may lead

		to a new boiler
The Stalled Sub-type: Lack of Finance *The house is a shelter*	Wants a warm, comfortable home, but is not extravagant in her requirements Wants to feel safe and secure in her home and be assured that any work undertaken is not ripping her off or putting her in danger Frugal and interested in saving energy primarily to save money. She is positive towards opportunities to improve the warmth and security of her home. Leaves parts of the house unheated through the winter, but uses draught-proofing to increase comfort	Limited to when grants are available Will undertake consequential improvements if dictated by grant scheme
The Stalled Sub-type: Pressures of Life *The house is a necessity*	Does not have the time, emotional energy or financial resource to undertake home improvements at present Will use a trusted, known professional to help with any essential jobs around the house but won't undertake any major projects May consider taking a loan to fund essential maintenance but they prefer to wait and use savings when they can afford	Almost none at present

Evaluation of the personas

To evaluate the personas further, the set was sent to a small number of key people to review and comment. These people included a research manager in the energy field, a customer insights expert working for a major utility company, an energy policy expert, an energy consultant and members of the academic project research team in which the study was conducted. All said that the personas described the range of owner-occupies well, in terms of their attitudes towards making home improvements. The feedback on the personas was generally consistent across all respondents, with positive comments from all. The personas were felt to 'bring the customer to life', allowing the user to see the person behind the data by providing value and richness to the core groups and making them relevant. All mentioned that income and the ability of the householder to pay could also have been included as a key variable. This could include an individual's access to finance, perhaps to indicate the kinds of measures that each persona could afford; however this aspect was outside the original study aims and so the data were not available when building the personas. Again, this is an area where further work could contribute. The respondents were also asked if they felt any key personas were absent. The most prominent omission was a persona relating to the social housing sector, and some respondents mentioned the private rented sector, particularly living in apartments. However, both these fell outside the scope of the original research which was focused on owner-occupiers. One respondent did suggest an 'Eco-Idealist' persona to parallel the Idealist Restorer. This persona was also identified by the researchers as missing from the set, as the small sample that provided the original data did not include anyone who had this characteristic, but anecdotally it was recognised as an archetype, which could present an example of an early adopter of new technology. Whilst this persona could represent an important stimulus to the market, as the personas were data driven, the Eco Restorer was not included to the original set, but further data collection could focus on this particular subtype to extend the set.

Discussion

The literature showed few categorisations of people in relation to home renovation to aid those developing energy efficiency interventions. However, the need to understand people's motivations and preferences is paramount if we are to encourage owner-occupiers

to refurbish their homes with energy efficient technologies, given the requirement for this group of householders to be proactive.

The developed set of personas presented here demonstrates that householders, even within the confines of owner-occupiers in solid-wall dwellings, are diverse and their goals and motivations need to be considered as subsets of the whole population. In some cases, the personas resonate with the limited findings from the literature. The Property Ladder Climber persona aligns with the 'mover renovators' identified by Baum & Hassan (1999) and the 'potential movers' (Munro & Leather, 2000); all have similar aspirations to renovate and move on. The desire to improve one's home, to increase its value or marketability (Earl & Peng, 2011) provides an important opportunity for policy-makers, as these people provide a stimulus to the market. Provision of finance through schemes such as the Green Deal should offer opportunity for the Property Ladder Climbers to undertake energy efficient renovations as part of their home improvements, as they are motivated to withstand the disruption and effort that may be involved.

The Affluent Service Seeker persona also wants to increase their property value, but in the longer term. They see their home as an investment for which they have worked long and hard and so its renovation is, as Munro and Leather concur, as much 'investment' as 'consumption' motivated. The inclusion of only two investment motivated personas in this set (Property Ladder Climbers and Affluent Service Seekers) also reflects the prioritisation of consumption motivated renovation. Based on this small sample, this suggests that developers of energy efficient interventions should recognise that some householders will want to undertake improvements that improve their quality of living, whether this is a warmer living environment, reduced bills, or improvement in the decor (perhaps through removal of mould or condensation), rather than increasing the value of their home.

This nest-building behaviour is evident in the Pragmatist personas, for both subtypes: Functional and Aesthetic. Priorities here are for a comfortable family home that meets the everyday requirements of the household. Homes were seen as central to the respondents' lives in Munro & Leather's (2000) research, with work undertaken on the home often seen completely independent to the value that the improvement might add. Energy saving

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technologies are only likely to be taken up if they fit in with the household's lifestyle; householders will not be tolerant to significant disruption if it upsets everyday life, unless the gains from the improvement impact on the space or comfort of the home. For example, external wall insulation that does not reduce room sizes or cause significant disruption to daily life during installation may be more acceptable than internal insulation that will impact in the short and longer term, even if it is cheaper to install and more efficient. Gram-Hanssen (2014) also identifies the prioritisation of indoor aesthetics and functions over energy saving renovations from her sample. Additionally, returning the home to its former (or improved) state of decoration as part of the job will be important to these personas. It would unacceptable to leave rooms needing finishing or redecoration after the installation of an energy efficiency measure. This would need to be provided as part of the job in order to fully meet the Pragmatist personas' needs.

In line with the findings of Williams (2008), the set of personas includes two subtypes that are Stalled – by Pressures of Life, such as illness, job or family changes; and by Lack of Finance. Whilst these two personas are unlikely to take on major renovation projects, they do provide future potential if their circumstances change. For some stalled households, the finance or capacity may return, once the temporary hurdle is overcome, or external finances can be provided, e.g. through the Green Deal. But for some, in particular older householders, this stalled position may be permanent. Munro & Leather (2000) also identify older householders with limited funds and lack of willing to face disruption, which could suggest a third 'stalled' persona who just do not want to renovate. This could be as a result of an inability to make a decision or simply lack of interest. Earl & Peng (2011) refer to people discounting the future 'hyperbolically, rather than exponentially', thereby giving undue weight to the immediate costs of home improvement. As a result, there is a cycle of continuous procrastination. For these owner-occupiers, policy offerings such as grant schemes may have no effect, regardless of their value.

It was evident from some of the interviews that some householders enjoyed the challenge of learning a new skill through DIY, or took pleasure from the completion of the renovation task. The Idealist Restorers persona demonstrates this most strongly, reflecting that the home improvement is an experience as well as a task, placing a high priority on quality.

Watson & Shove (2009) talk of the value in developing a competence or skill and Gram-Hanssen (2014) identifies that renovation can be a creative task which some people relish; these are key features of the Idealist Restorer persona. These people are unlikely to allow a tradesperson to undertake significant work on their home without close consultation and supervision. Tradespeople making energy efficient renovations will need to ensure they are expertly skilled and prepared to work closely with this type of person in order to complete a satisfactory job. The Affluent Service Seeker is less likely to undertake work themselves and requires the tradesperson to be reliable, trustworthy and produce work of a high quality; in return this persona will pay for the service. Munro & Leather (2000) report serious problems in finding a competent and trustworthy builder, which is a key requirement for these two personas.

To develop the understanding and application of the personas further, each has been considered in relation to a particular intervention – the installation of external wall insulation, a particularly relevant measure to the solid-wall properties owned by the participants in this study. Consideration of this measure for each persona and the design and policy implications, developed from the authors' immersion in the data and understanding of the measure in practice, are set out in Table 2.

Table 2. Possible impact on each persona of External Wall Insulation (EWI) as a renovation measure

Persona (inc. sub-type)	Requirements of the persona from external wall insulation	Implications for policy and technology design
The Idealist Restorer	The Idealist Restorer will only be interested in EWI if it will maintain the traditional appearance of the property, including being sympathetic to any architectural features. This may require use of traditional materials as a veneer and specialist detailing. The Idealist Restorer will be positive about the benefits from this new technology but will want to understand the detail of the process and benefits in advance.	The advantages and disadvantages of EWI must be made explicit in advance and in detail. This might require the provision of expert, independent, but bespoke, advice relating to the issues of older properties in particular It must be possible for EWI to be fitted without losing architectural or aesthetic features of the property. EWI must be offered in a range of finishes, including the use of traditional materials. The use of traditional finishes must meet the approval of planning requirements. Policy measures must allow part-DIY installation so that the Idealist Restorer can be remain in control of the retrofit. This persona may take years to decide to install this measure and will only proceed when they feel they have adequate information and time available to dedicate themselves to the project.
The Affluent Service Seeker	The Affluent Service Seeker is likely to be open to the technology and, in particular, the benefits it brings. The Affluent Service Seeker is likely to want a complete package from one supplier, including preparation, repainting and restoration of items such as guttering, house numbers etc. and will be willing to pay for this service.	Accredited suppliers must be skilled to supply a range of services, or work under a project manager who can draw these together seamlessly, as a 'one-stop shop'. Financial penalties could be applied if EWI is not fitted to an agreed timeplan, extending the accreditation requirements already in place. EWI must be available in a range of quality finishes to

Persona (inc. sub-type)	Requirements of the persona from external wall insulation	Implications for policy and technology design
	Energy saving will not be the primary objective of the refurbishment. EWI must improve the indoor environment, in particular comfort levels. EWI must add financial value to the property in the medium to long term. As this persona has little tolerance to extended periods of unplanned disruption, projects must run to plan.	ensure the look of the property is not compromised. Energy saving is likely to be a blind spot for this persona as comfort and property value are primary concerns. Interested in the Green Deal if it makes financial sense, but likely to have access to better loan rates elsewhere or personal savings.
The Property Ladder Climber	The Property Ladder Climber's primary requirement is for enhancement of the property value, so EWI must add financial value to the property in the short term. Increased saleability of the property is also key and so the appearance of the property must be enhanced by EWI.	Finance schemes must offer short term benefits and must not put off future buyers through perceived long term burdens. Policy measures must allow part-DIY installation so that the Property Ladder Climber can minimise costs. Energy saving is of little importance to this persona, unless it relates to improved saleability of the property. Policy measures that relate to energy performance will need to be mandatory in order for this persona to respond.
The Pragmatist Sub-type: Functional	The Functional Pragmatist is most likely to consider EWI as part of a wider renovation project, for example when adding an extension to the property. The Functional Pragmatist will enjoy the improved comfort of the home, without the loss of internal space, but the EWI must not compromise usable garden or passageway space outside as these outdoor spaces may	The Pragmatists will be cautious about taking on loans for large renovation projects and so financial packages must be competitive with other loans available and could reward part payment from savings. The Green Deal packages may not be competitive, given the likely potential for this type of persona to extend their mortgage at a more favourable interest rate.

Persona (inc. sub-type)	Requirements of the persona from external wall insulation	Implications for policy and technology design
	be important to family living, e.g. patio use or for pushchair or bicycle access.	To appeal to this type of persona, EWI will need to be provided as a complete package, perhaps including redecoration to complete the job, under a project manager who guarantees the quality and time completion of the work.
The Pragmatist Sub-type: Aesthetic	The Aesthetic Pragmatist may also consider EWI as part of a wider renovation project, but will have an enhanced focus on the appearance of the property. Although there will not be such a focus on traditional features as the Idealist Restorer, it is important for the renovated property to look neat and tidy, as well as saving energy and improving comfort.

As this persona has little tolerance to extended periods of unplanned disruption, projects must run to plan. | The appearance of the EWI will be of less importance to the Functional Pragmatist, but energy saving, cost and expediency of the retrofit will be key.

The Aesthetic Pragmatist will want EWI that looks smart and performs well, but will focus more on value for money than the traditional appearance of the finish, |
| The Stalled Sub-type: Lack of Finance | The persona Stalled by Lack of Finance will consider EWI only if it is available by means of a grant.

They will appreciate the long term benefits of improved comfort and, possibly reduced bills, (depending on take-back), but will not be in a position to renovate without external support. | There are limited opportunities for these Stalled personas, unless policy measures can provide 100% finance and practical support through delivery of a renovation service. This still may be too difficult for some to take on, as other pressures mean that they will not improve the energy efficiency of their properties under any circumstances. The only options for these people is to wait until they move out of this persona type, or provide measures that will assist them to do this. |
| The Stalled Sub-type: Pressures of Life | Those Stalled by Pressures of Life may be interested in the benefits of EWI, but have little or no capacity at present to undertake a renovation project, even if it is at no cost. Essential repairs only will be made. | |

A number of the developed personas have little interest in energy saving, and none see this as the primary motivator for renovation. This has obvious implications for policy and design measures that are aiming to reduce carbon emissions and presents a significant challenge. The personas provide insights into other motivations for householders which can perhaps be used as opportunities to encourage engagement with energy saving retrofit as a by-product. However, there remain some owner-occupiers that will never engage in renovation, perhaps as their circumstances mean they remain stalled or because they see no short or long term reason. Those who are elderly may feel their life expectancy is too short to make a long-term measure worthwhile and so policy measures that provide short term payback (not necessarily financial) will be needed to encourage these people take the decision to renovate their properties. These measures might include cashback incentives or measures delivered as a package that promotes the provision of warmth and comfort rather than energy saving.

The persona set developed from this study has similarities to the some of the types of home improvers described in the literature, but have extended the detail for this particular context and brought together the rather disparate existing knowledge into one resource. Whilst elements of the Property Ladder Climbers and Stalled personas are more clearly identified in previous literature, the requirements of the Pragmatists, Affluent Service Seekers and Idealist Restorers are novel. Gram-Hanssen's (2014) survey of Danish householders identifies people renovating their property as a continuous activity, but recognises that these people will have varying goals and motivations. The importance of understanding lifestyles, status and consumer choice as part of the renovation process is key. Gram-Hanssen notes, importantly that, in most cases, energy efficiency is not the main renovation rationale, which continues to present a challenge to the policy-makers and technology developers alike.

This persona set describes individuals, but it is likely that a household will comprise of more than one persona type within the decision-making team. It was evident from the interviewed sample that couples had different approaches to home improvement, representing different, sometimes conflicting, personas. This can create tensions where there is disagreement in priorities and can cause stagnation where two or more parties

cannot reach agreement on how to proceed. In some cases, a shared decision can be made, but this could be a compromised decision, resulting in a less than ideal outcome. In other cases, there may be a dominant decision-maker whose preferences take priority. Attempts to develop mass customisation approaches to domestic retrofit have been explored, e.g. by E.ON (Madlener, 2013) where they identified the importance of the householder as the decision-maker, by presenting them with a range of retrofit packages to suit their individual behaviour and house, which enables the customer to participate in the design of the retrofit package, ensuring it meets their needs.

Conclusions

The personas presented in this paper have been created from detailed qualitative data from a small sample of people who live in owner-occupied, solid-wall dwellings in the UK. They provide an insight into the different types of householders in relation to home improvements. This enables the creation of a more targeted and tangible representation of end users when considering energy efficient interventions. The personas can be used by policy-makers to consider how future policies might be taken up by different sectors of the population, especially important when energy saving is not a priority for home owners. Supported by quantitative market segmentation data, this could provide clear insight into the penetration of future policies. Energy providers can use the personas to develop business models that relate to specific parts of the market, testing their potential by considering the core customer groups. Similarly, designers and technology developers can use the personas in the early stages of development, to ensure they have a target user in mind. This will prevent energy technologies from being developed blindly, with no mind to the likely users; rather, as one of the respondents in the evaluation said: 'to focus engineers on people'. They provide an insight into the range of different types of people, so that they are not treated as a homogeneous group, and so solutions to aid domestic energy renovation are better targeted to owner-occupiers and more likely to be successfully adopted.

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Notes

1 The Standard Assessment Procedure (SAP) is the methodology used by the UK Government to assess and compare the energy and environmental performance of dwellings.

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PUBLICATION H

Banfill, P.F.G., Simpson, S.A., Haines, V.J.A., Mallaband, R.A.L., 2012. Energy-led retrofitting of solid wall dwellings – technical and user perspectives on airtightness. Structural Survey: Journal of Building Pathology and Refurbishment, 30 (3) 267-279.

Abstract

Purpose – Mechanical ventilation with heat recovery (MVHR) is increasingly being promoted in the UK as a means of reducing the CO2 emissions from dwellings, and installers report growing activity in the retrofit market. However, the airtightness of a dwelling is a crucially important factor governing the achievement of CO2 reductions, and the purpose of this paper is to understand the technical implications of airtightness levels in an experimental dwelling, purpose built to typical 1930s standards, at the same time as gaining the users' perspectives on airtightness and ventilation in their homes.

Design/methodology/approach – In-depth interviews were carried out with 20 households to collect information on their retrofit and improvement strategies, attitudes to energy saving and their living practices as they impinge on ventilation. The experimental house was sealed in a series of interventions, leading to successive reductions in the air permeability as measured by a 50 Pa pressurisation test. The behaviour of a whole-house MVHR system installed in the experimental house, was simulated using IES Virtual Environment, using a range of air permeability values corresponding to those achieved in the retrofit upgrading process.

Findings – In the house considered, air permeability must be reduced below $5m^3/m^2h$ for MVHR to make an overall energy and CO2 saving. However, to achieve this required a level of disruption that, on the basis of the views expressed, would be unlikely to be tolerated by owners of solid wall dwellings.

Originality/value – The paper is the first to combine results from a user-centred approach to exploring the existing practices of householders with a simulation of the energy and CO2 performance at different levels of airtightness of an experimental house in which MVHR has been installed.

Keywords

1 Introduction

The UK has the oldest housing stock in the developed world (Energy Saving Trust, 2003). Of 25 million dwellings in the UK, 34% have solid walls and are responsible for 50% of the total UK domestic sector CO_2 emissions. In a typical unimproved UK solid wall dwelling the ventilation heat loss rate is approximately equal to the heat loss rate through the fabric (walls, roof and ground floor) so, in the context of Government targets of reducing CO_2 emissions from buildings, reducing this ventilation heat loss is attractive and the Energy Saving Trust (2005) emphasises the importance of improving the airtightness of dwellings. Since mechanical ventilation with heat recovery (MVHR) is an established contributor to achieving the zero carbon homes standard required by UK legislation for all new homes by 2016, including those reaching Passivhaus standards, there is an emerging market for MVHR in retrofit installations. However, it is much more difficult to achieve the required low levels of air permeability by retrofitting an existing dwelling than when building a new one, and it is not clear to what extent users and specifiers of retrofit MVHR systems realise how important the building's airtightness is in achieving the anticipated savings. Understanding the technical implications and the user perspectives on airtightness is therefore necessary to prevent inappropriate advice, potentially leading to undesirable disruption and expensive mistakes, being given.

This paper describes some of the work in progress as part of a consortium project entitled Consumer appealing low energy technologies for building retrofitting (CALEBRE - www.calebre.org.uk), which aims to establish a validated, comprehensive refurbishment package for reducing UK domestic carbon emissions, that is acceptable and appealing to householders, and specifically targeted at UK owner occupied solid wall properties (classified as 'hard-to-treat'). It is investigating a selection of technologies, informed by the reality of the user perspective, addressing such questions as the degree of disturbance that householders are prepared to tolerate during a refurbishment programme. Some of the retrofit solutions have been installed and are being evaluated in a newly-constructed test house (the E.ON 2016 House, Figure 1), specially built in 2008 to 1930s standards at Nottingham University. This house has cavity walls which are assumed to have similar performance, when the cavity is filled, to solid walls with external insulation, and there is no

reason to expect the air permeability to be different in the two cases. This paper describes results in two main areas, (i) the importance (and difficulty) of achieving airtightness in reducing heat losses and CO2 emissions from dwellings and (ii) homeowners' perspectives on this aspect of the retrofitting of their homes.

2 Indoor air quality, ventilation and airtightness

2.1 Technical background

Ventilation is needed to dilute and remove pollutants produced indoors, such as moisture, body odours, cooking smells and volatile organic compounds, as well as to supply fresh outdoor air (Awbi, 2003). If moist air comes into contact with a cool surface, the local relative humidity increases, and when it exceeds 80% the risk of mould growth increases rapidly (Roulet, 2001). Any surfaces below the dew-point temperature will permit condensation to form, a serious problem with uninsulated external walls. The development of damp, mould and fungi can result in health and comfort issues for occupants, therefore it is important for the ventilation strategy to maintain RH levels between 30-70% (Carrer *et al*, 2001). This means that in general the ventilation rate is greater than that required merely to supply fresh air (Energy Saving Trust, 2003). For dwelling renovation, therefore, it is important to consider the ventilation strategy when implementing measures to improve the building airtightness to ensure there is no detrimental effect on occupant comfort or the building fabric.

The UK's relatively mild climate means dwellings predominantly rely on uncontrolled natural ventilation. This does not guarantee a sufficient air change rate to maintain indoor air quality all year round, but allows excessive ventilation and heat loss in windy conditions. Until the recent drive towards low carbon housing, the airtightness of UK dwellings showed little improvement. In a survey of 471 dwellings (Stephen, 1998) those constructed between 1900-1930 had a mean air permeability just over 10 air changes per hour (ach[-1]) at 50 Pa, measured by the pressure test (CIBSE, 2000). For a sample of houses built 1930-1960, it exceeded 15 ach[-1], while in the most recently constructed properties it had returned to 10 ach[-1]. In other parts of Europe dwellings are much more airtight and mechanical ventilation (with or without heat recovery) is universal. It should be noted that the 50 Pa value,

specified in standards, is different from the unpressurised infiltration rate that should be used in thermal energy calculations. Kronvall (1978) derived a 'rule of thumb' method in which the natural infiltration rate is 0.05 times the tested air change rate. In this paper, all measured air change rates and permeabilities are 50 Pa pressure test values.

Passivhaus standards (2011) specify 0.6 ach^{-1} at 50 Pa and were developed to enable the design and construction of dwellings with annual heating or cooling energy consumption below 15 kWh/m^2 treated floor area. At this level, the ventilation system can address the space heating needs and a whole house MVHR system is an essential component of this strategy. Although strictly these standards apply only to new buildings, they are increasingly being implemented in refurbishment projects, and the first certified Passivhaus retrofit in the UK was recently achieved for a terraced Victorian property (Octavia Housing, 2011).

The heat recovered from the ventilation air by MVHR offers a modest contribution to CO2 emissions savings. As a result the market for MVHR systems in the UK has been stimulated and in 2009 was estimated at 15000 units annually, worth £30million. Of this the retrofit sector accounts for a small but growing share of about 5% (Waddell, 2010). Since the effectiveness of an MVHR system depends on the correct balance between heat recovery efficiency, fan efficiency, air flow rate and building airtightness there is a technical challenge in using MVHR for retrofit. Since there was no prior information on this, the technical objective of this investigation was to establish the airtightness level that must be achieved in order for MVHR to have a significant effect on the CO2 emissions, using both modelling and monitoring.

Macintosh and Steemers (2005) found differences between the expectations and reality for an MVHR system in housing in four areas:
1. Noise – disturbance from external noise and pollution should be improved, but residents in the study reported noise from inlet vents which was unwanted.
2. Perceived freshness – ventilated air may not be perceived as fresh as it is not at external temperature and no direct connection to the outside (for example via a window) was made by residents.

3. Perceived control – residents opened/closed windows much more frequently than they made adjustments to the MVHR controls.

4. Misunderstanding – residents misunderstood what the ventilation was for and when it should be used.

In light of this, the behavioural objective of the investigation in this paper was to compare the technical findings with user perspectives in order to identify acceptable ways forward.

2.2 User centred design background

For any new technology to be successful, it must be accepted by the end users and meet their needs. These needs include their social, emotional, practical and economic needs. For a technology such as MVHR, it is critical that it is considered in context of the built environment and the end users, that is householders. By taking a user centred design approach, it should be possible to explore the existing ventilation practices of householders and identify requirements for the technology that will meet these requirements in context. The principles of user centred design are generally accepted to be an early focus on users and tasks, empirical measurement and iterative design (Gould and Lewis 1985), leading to the design of useful, useable and desirable products. Preece *et al*. (2002) propose that providing "an easily accessible collection of gathered data" will help designers remain focused on user needs. Clear communication of requirements to designers and technologists in a way that is meaningful and relevant is therefore a crucial component of user centred design. To this end, CALEBRE is taking a user led approach to understanding householders with the intention of ensuring that the resulting technologies are designed to be acceptable and appealing.

3 Research Methodology

3.1   Summary of the CALEBRE project

The CALEBRE project aims to develop a number of technologies suitable for retrofitting to solid wall dwellings. These are at various stages of completion and will be tested either in the laboratory or in service in the E.ON 2016 house. In addition to the work described in this

paper, there are a number of technological workpackages, which can be summarised as follows:

- Develop an electric air-source heat pump, able to deliver hot enough water to make it suitable for replacing the boiler in an existing central heating system.
- Develop a gas-fired air-source heat pump, able to deliver hot enough water to make it suitable for replacing the boiler in an existing central heating system.
- Develop vacuum double and triple glazing units, able to achieve U-values of 0.33 $W/m^2.K$ or less, suitable for use in conventional windows.
- Develop advanced surface treatments for internal walls, with hygrothermal properties able to smooth the changes in air temperature and relative humidity.

In addition, the project will explore the market development issues associated with mass production of these novel technologies and develop a prototype selection tool, informed by the identified needs of homeowners. The project has a strong consumer focus and a group of householders has been recruited to participate in the evaluation of the technologies and their implications for user behaviour and performance in service.

3.2   Airtightness measures

Air permeability tests using the 50 Pa fan pressurisation technique (CIBSE, 2000) were carried out on the E.ON 2016 house in its initial state and following each stage of the application of a series of retrofit solutions (Table 1), installed over several months with the aim of reducing the level of uncontrolled ventilation. This provided a series of measured permeability values which could inform the infiltration value used in a dynamic thermal model of the house to assess the impact on the annual energy consumption and CO2 emissions. Some of the upgrades to the external fabric and glazing have multiple benefits in that they contribute to reduced infiltration rates as well as conduction losses. Measuring the changes in the building's air permeability allows the combined effect of these improvements to be assessed as a series of retrofit measures by updating these properties simultaneously in the thermal model.

3.3   Dynamic Thermal Modelling

Dynamic thermal modelling software (IES Virtual Environment) was used to build a model of the E.ON 2016 house (Figure 1) to simulate a year's operation and calculate the annual energy consumption and CO_2 emissions. Details of the building geometry and orientation were input using the architectural drawings to create zones corresponding to each room and represent the building. The Nottingham Test Reference Year weather file (CIBSE, 2008) was used to simulate local climatic data.

Figure 1. E.ON 2016 house at The University of Nottingham and the IES VE Dynamic Thermal Model

The operational parameters for each room type were derived from the National Calculation Methodology database (NCM, 2010) to develop a set of templates representing the occupied house, specifying heating set-points, domestic hot water consumption and internal gains (lighting, equipment and occupancy), as well as diversity profiles set up to represent daily and weekly variations in these values.

These parameters were consistent for all the analyses so that the variations in energy performance would be attributable to the ventilation strategy and the thermal properties of the building. The thermal modelling assumes that there are no changes in the internal conditions before or after the application of the retrofit measures, and that occupants do not take the benefit of higher living temperatures. This may be wrong, as research into this 'rebound effect' shows (e.g. Sorrell, 2009), but will not be considered further here.

Construction templates were created defining both the internal and external constructions, and performance characteristics. This allowed the changes in U-value between the initial base case house, as built to 1930s construction standards, and the thermally upgraded construction, as per the improvement work carried out as part of the retrofit process, to be replicated in the E.ON 2016 dynamic thermal model. This would simulate the differences in conduction losses associated with the improved glazing and building fabric.

3.4 Understanding of User Requirements

To understand the requirements of the users in context, twenty households (with 66 permanent occupants) were recruited to take part in a series of data collection activities. Each household lived in an owner occupied, solid wall house in the East Midlands region of the UK. A purposive sampling approach was taken, to ensure inclusion of a range of house types (detached, semi-detached, link, mid and end terraced), household types (single, couples, families with young, older and grown up children), participant age ranges (28 – 80 years old), income bands (under £10,000pa – over £70,000pa) and location (urban, suburban, rural). While not intended to be a statistically representative sample, it allowed detailed exploration of a snapshot of different domestic situations.

Two in-depth interviews were undertaken with all adult household members wherever possible to ensure a whole household perspective. The first interview explored reasons for buying the property, improvements made to the house and issues relating to these (who did the work, levels of disruption, approximate cost, etc). These were drawn up with the householders using an innovative 'timeline tool', reported in more detail in Haines *et al.* (2010). Issues relating to comfort and home improvement aspirations were also covered. In the second interview, attitudes towards energy saving were explored, the CALEBRE technologies were described to the householders and initial responses obtained. Questions were then asked about the householders' various practices in the home that related to the design of the technologies. These were intentionally focused on the householders and their home lives to ensure a relevant and engaging conversation, rather than a more formal question and answer session. Finally a tour was made of the home to see in detail aspects of the house that had been mentioned in the discussions, as well as to take a photographic record of the various features. Digital audio recordings from these interviews were

transcribed and analysed using NVivo 9. Conversational extracts relating to ventilation and related practices were analysed in detail and the key findings are presented in this paper.

4 Results and Discussion

4.1 Air permeability

Each set of improvement measures applied to the E.ON 2016 house contributed to a reduction in the building's air permeability, but with variable success (Table 1). In its original state the house was very leaky and the extensive stage 1 improvements were expected to significantly reduce the measured air permeability but succeeded in reducing it only from 15.57 to 14.31 m^3/m^2.h. The relationship between permeability in m^3/m^2.h and air change rate is specific to the geometry of the building: in this case 15.57 m^3/m^2.h = 14.85 ach^{-1}. Noting the inconsistency with air change rates mentioned earlier, we report permeability values here because they are familiar to UK professionals. Inspection revealed that the draught-proofing had been poorly applied to the windows and doors, often with an incomplete seal around the perimeter of the component, and installing the MVHR system had created new gaps in the building envelope and duct connections to the rooms, permitting uncontrolled airflow. In stage 2 the draught-proofing was re-done and extended to the remaining doors and windows, reaching 9.84 m^3/m^2.h. The building air permeability was further reduced by the two remaining stages, culminating in the final measure of sealing and insulating the ground floor, which achieved the final building air permeability value of 5 m^3/m^2.h at 50 Pa.

Much effort and cost was needed to reduce the air permeability and the research team were surprised at how poor was the workmanship in the initial stages of draught-proofing, undertaken professionally to current industry standards. Gaps were left around doors and previously installed insulation disturbed by later work. The final stage was especially disruptive and involved lifting floor coverings and furniture before installing a membrane over the timber floor. The total cost of draught-proofing exceeded £12000, and with the MVHR installation costing £6000 this is unlikely to be economic.

While sealing a house is perceived as a simple task, it is in fact much more challenging because of the care and attention to detail needed by the workforce. Air permeability is made up of a myriad of entry points in the fabric, which can be created by oversize holes for pipes and wiring, irregular gaps between new windows and brickwork openings, gaps between walls / floors and walls / ceilings, etc (Energy Saving Trust, 2005). Suspended timber ground floors can be a particular problem and in this case success was achieved by installing a membrane across the boarding, which was dressed up behind the skirting boards.

Table 1. E.ON 2016 house measured air permeability values

| Stage	Air permeability at 50Pa ($m^3/m^2.h$)	Description of work
As built	15.57	Single glazed windows Uninsulated walls, floor and roof space No draught-proofing
1	14.31	Double glazing installed Insulation applied to walls and loft Draught-proofing applied to windows (excluding kitchen, bathroom and WC) and doors Installation of whole house MVHR system
2	9.84	Kitchen, bathroom, WC windows and under croft trap-door draught-proofed Draught-proofing throughout house re-installed Window trickle vents blocked up
3	8.60	Service risers sealed Pipework penetrations sealed (radiators, water pipes etc.) Sealing around boiler flue Covers fitted to door locks Kitchen fan removed and bricked up
4	5	Suspended timber ground floor insulated and sealed

4.2 Heat losses, energy consumption and CO2 emissions

Full details of the dynamic thermal simulation and energy modelling have been reported elsewhere (Banfill *et al.*, 2011) and are summarised here. Figure 2 details the disaggregated loads on the heating system at the time the peak space heating load occurs in the dynamic analyses. Note that, as the final retrofit measure is applied the peak load occurs at a different time of year. The results show the expected significant reduction in energy consumption as a result of the work, but since the focus of this paper is on airtightness, these will not be considered further. Note that measured thermal energy data is not yet

available, since performance monitoring is still in progress. Comparing the performance of the building after stage 4 with the base case as built shows an overall 71% reduction in total annual building energy consumption from the base case. This takes into account the energy associated with the space heating, domestic hot water, auxiliary (fans and pumps), lighting and equipment.

To investigate the effect of MVHR alone (i.e. separate from the other measures listed in table 1), a modelling study starting from a naturally ventilated base case of 10 m^3/m^2.h (based on the recommended ventilation rate as advised by BRE Digest 398, where Kronvall's rule of thumb has been used to determine an equivalent air permeability value), simulated its effect on energy and CO2 emissions at successively reduced air change rates, culminating in the Passivhaus standard of 0.63 m^3/m^2.h (0.6 ach^{-1}) and the results are given in Table 2.
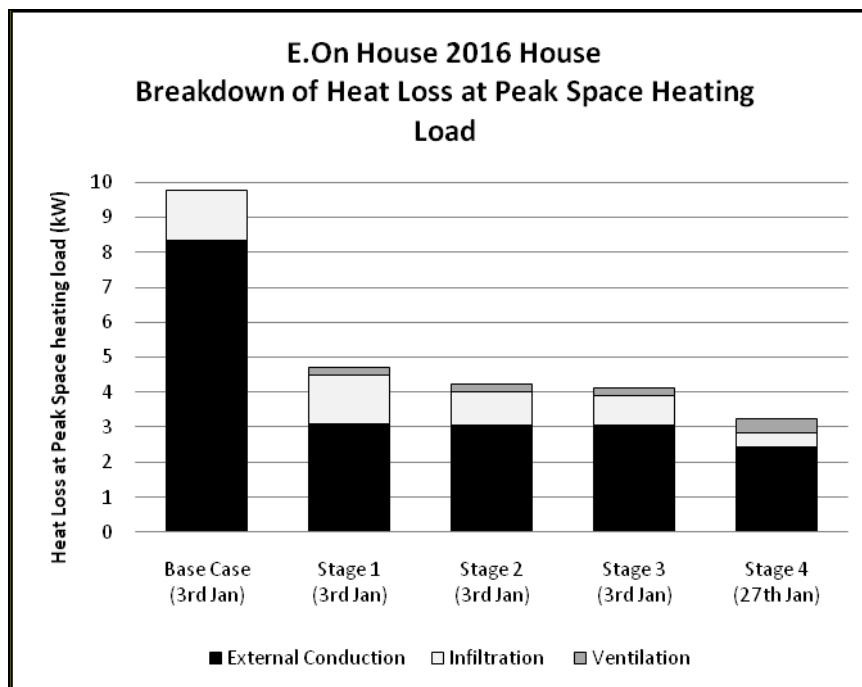
Figure 2. E.ON 2016 House: breakdown of heat loss at peak space heating load

It may be recalled that stage 4 of the retrofitting measures achieved a 50 Pa air permeability of 5 m^3/m^2.h. At this level the annual energy consumption is barely reduced and the CO2 emissions are still above the unimproved house. Further improvements in air permeability would be necessary to effect a significant reduction in energy and CO2 but even at 0.63 m^3/m^2.h, the Passivhaus level, annual energy consumption is only 11.7% lower and CO2 emissions are only 5.3% lower.

The carbon intensity of the electricity used to operate the MVHR system is about three times that of the gas used for heating and this means that achieving an overall reduction in the building's CO_2 emissions requires the space heating demand to be reduced by three times the electricity consumption of the MVHR system.

4.3   Householder preferences and practices

Achieving an airtight house may be a desirable approach from the perspective of saving heat loss and hence CO_2 but any system, particularly one that will be retrofitted, must meet the householders' requirements or else it will not be appealing nor acceptable. The practices and preferences obtained from the householder interviews uncovered a range of issues that may result in an unappealing system, or one that works sub-optimally. These are discussed below. Whilst many of the homes had some double glazing and loft insulation, none had more advanced energy efficiency measures installed. None had attempted to actively reduce the air permeability of their home (although attempts to reduce draughts had been made through fitting double or secondary glazing, by using carpets and soft furnishings and by blocking up chimneys). None of the houses had an MVHR system.

Table 2. Impact of airtightness on modelled annual energy consumption and CO$_2$ emissions of the thermally upgraded E.ON 2016 house using an MVHR system specified to best practice standards

Study	Annual space heating energy (kWh/m^2)	Annual auxiliary energy (kWh/m^2)	Total building annual energy consumption (kWh/m^2)	% change (energy)	Total building annual emissions (kg.CO$_2$/m^2)	% change (CO$_2$)
10 m^3/m^2.h naturally ventilated	65.7	9.6	126.9	0	44.6	0
10 m^3/m^2.h with MVHR	76.4	10.8	138.8	+9.4%	47.4	+6.2%
7 m^3/m^2.h with MVHR	66.3	10.8	128.8	+1.5%	45.4	+1.7%
5 m^3/m^2.h with MVHR	62.9	11.4	125.9	-0.8%	45.0	+0.9%
3 m^3/m^2.h with MVHR	56.5	11.4	119.5	-5.9%	43.8	-2.0%
1.05 m^3/m^2.h with MVHR	50.3	11.4	113.3	-10.7%	42.6	-4.7%
0.63 m^3/m^2.h with MVHR	49.0	11.4	112.0	-11.7%	42.3	-5.3%

Air flow and freshness

Many householders were keen to maintain air flow within their homes, even if it meant obvious heat loss. Current approaches to controlling air flow included opening and closing doors, windows or vents, or closing curtains to block off draughts. One participant spoke of the more refreshing *"natural feeling of a breeze"* (Male, age 29) and airtightness was seen as a negative issue: *"I like to be able to breathe fresh air. I don't know if I'd really want an airtight house"* (Female, age 61). Associations were made with the environment within an aeroplane, with words such as *"recycled"*, *"stale"* and *"manky"* being used to describe their expectations of a mechanical ventilation system. When an MVHR system was explained to householders in more detail, the idea was more positively received (particularly in relation to some of the other technologies presented) and so there is clearly potential for successful systems once the initial preconceptions are overcome.

Open fireplaces

Of the 20 houses surveyed as part of the project, 15 had some form of open chimney or vent for a wood burning stove. Of these houses, 9 of the householders said they would not be prepared to consider losing the functionality of all their fireplaces (even if they were able to keep the fireplace aesthetics). Some were prepared to lose the functionality of some of the fireplaces, but not all. The majority of households viewed the fireplace as an occasional 'treat' rather than the standard method of heating the home. Its use was described by one householder as *"High days and holidays – not very often"* (Female, age 51). However there were households in the sample that used their fireplaces every day during winter. Although householders may be aware that the fireplace inhibits the airtightness and increases draughts, they were still unwilling to remove its functionality and instead prefer to use temporary blocks for the chimney when it is not in use, as illustrated by this comment: *"The only thing that would not be airtight...would be the fire place because there is no balloon in or cap or anything like that, so that can be quite draughty in winter, but we stick a black bag full of newspaper up there don't we, when we're not using it"* (Male, age 29). Those householders that would be happy to lose the functionality of their chimney expressed a desire to keep the aesthetics of the traditional fireplace in order to maintain the period features of their home. Although some of the houses had fireplaces in upstairs rooms, none were used; when questioned, this was due to safety, and so could easily be made airtight.

Door opening practices

A retrofitted MVHR system is likely to require a good circulation of air within the home (as a more limited venting system will be easier and less disruptive to install) and so internal door opening practices were explored. Householders reported strong habitual practices, for example always closing certain doors at night time, or leaving doors ajar at certain times of the day. Reasons for habitually closing internal doors included to reduce internal noise (from other members of the household, or a striking clock), to stop dust circulating through the house, to keep pets and young children in particular areas of the house, for privacy or to keep light out, or to shut off part of the house, either when a child has grown up and moved away, or when only certain rooms are heated. This final practice was common in houses where householders did not heat their whole house every day (perhaps only doing so when guests were visiting) or to keep the heat from an open fire within a room for the *"cosy*

family stuff" (Female, age 51). Internal doors were sometimes left open by householders as a regular practice, or were so poorly fitting that air would circulate past them easily even if closed: *"When they do shut they have got gaps haven't they"* (Female, age 43).

Damp

Many of the householders had damp areas in their homes and used ventilation as a means to control humidity. This may be as a short term measure (e.g. after a shower) or longer term, with the regular use of a de-humidifier. Whilst many householders recognised they had a draughty house, there was a feeling that the draughts kept the house adequately ventilated and healthy. The need for a system to replace what occurred naturally was not recognised. Communicating the benefits of an airtight house with MVHR system is critical to win over these householders.

4.4   General discussion

Achieving airtightness is clearly important for reducing heat losses and CO_2 emissions and MVHR can contribute to savings but levels sufficiently low for MVHR to be effective are very difficult to achieve in older properties, as demonstrated by the number of stages needed for sealing the E.ON 2016 house. In addition, people have features in their older homes that mean airtightness is difficult to achieve, in particular open fireplaces that are used regularly in the winter. They may be willing to block these (using a balloon or similar) in the summer but this is not the time when it is needed.

Retrofitting an MVHR system will probably mean a reduced number of vents, because the likely whole house disruption that will be caused by a more integrated system is unwelcome to householders unless they are doing total renovations. However, our study of 20 households suggests that whole house renovation is uncommon other than at the time of purchase (and even then not all householders did this).

Attitudes towards an MVHR system are initially negative: people like fresh air in their home, which they feel is necessary to deal with issues like damp and condensation, as well as a perceived negative effect on health through germs being recirculated. When it was explained to them, householders were more positive about MVHR, appreciating that it

could help their damp problems and that the same air was not recirculated, and so the benefits would need to be clearly communicated. However, people have habitual internal door opening / closing practices that mean that air flow within the house may be limited (closing doors for privacy, keeping pets or children contained, etc), which could limit the effectiveness of an MVHR system.

5 Conclusion and Further Research

Airtightness is a crucial factor in achieving energy and CO_2 emissions reductions in dwellings and it is easy to over-estimate the reductions achievable by retrofitting MVHR. Even with equipment specified to best practice standards the air permeability measured at 50 Pa must be reduced to less than 5 m^3/m^2.h to reduce annual building energy and to still lower values to reduce annual CO_2 emissions. This difference is due to the CO2 intensity of the electricity used to power the MVHR being higher than the CO_2 intensity of the gas saved by reducing the heating energy use. We look forward to being able to compare these modelled predictions with measured data in a future paper, but in the meantime there is clearly potential for over-selling of the merits of MVHR in a retrofit situation. In a context where Green Deal-type incentives are offered for energy-reducing retrofit measures it would be unfortunate if householders used up their credits by installing MVHR early in a sequence of interventions. Other more cost-effective approaches to achieving energy efficiency in dwellings should receive preference, and this point should be considered by those responsible for setting up incentive schemes for householders.

Achieving such low air permeability in existing dwellings appears to be challenging even to experienced installers of draught proofing, because of the high level of care and attention to detail required. In the case of the E.ON 2016 house it was necessary to rigorously seal the entire ground floor, as well as the various penetrations of the building envelope, in order to reduce the permeability to 5m^3/m^2h. This is an important and worrying finding and suggests that it would be advantageous to set up a competence scheme for installers of draught proofing. The importance of air permeability to energy reduction suggests that airtightness testing should be made a mandatory part of all energy-led retrofit programmes.

Technically, the installation of MVHR in the E.ON 2016 house was carried out with levels of workmanship that fell short of those that would be necessary to achieve the energy savings anticipated. Thermographic imaging showed significant heat loss due to incomplete insulation around ducts and penetrations. Design of a retrofit MVHR installation is likely to be a compromise because of the difficulty of installing supply ductwork in the optimum locations. Air quality measurements in progress to confirm or refute this will be reported in a future paper. All this points to the risk of MVHR underperforming in retrofit applications.

The householder surveys showed that occupants value the very features in their homes that make achieving airtightness difficult, in particular the importance of fireplaces and their availability for use on special occasions or as a focal point for the family. Strong negative perceptions of MVHR were held because of its association with staleness and lack of fresh air whereas, in contrast, it is a source of controlled fresh air which offers the potential for reduction of damp conditions and removal of pollutants. This suggests that there might be situations where positive communication of the benefits of MVHR would change the attitudes of householders.

Finally, achieving the levels of air permeability at which MVHR is of benefit to energy and emissions involved a prolonged and ultimately disruptive process of works. If this were always to be the case, retrofit installation of MVHR would be confined to those occupants who were undertaking a total package of measures, for whom the added disruption would not present a problem. The household survey suggested that such people are in a minority: the majority of householders would not tolerate such disruption.

6 Acknowledgement

7 References

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Vadodaria, K., Loveday, D.L. and Haines, V. (2014). Measured winter and spring-time indoor temperatures in UK homes over the period 1969 to 2010: a review and synthesis. Energy Policy 64 pp 252-262.

Abstract

This paper presents a review and synthesis of average winter and spring-time indoor temperatures in UK homes measured over the period 1969 to 2010. Analysis of measured temperatures in a sample of solid wall dwellings in the UK, conducted as part of the CALEBRE research project, is included. The review suggests that, for periods when occupation was likely, there has been little or no increase in winter and spring-time average living room temperatures over the last 40 years, with average recorded living room temperatures having been historically lower than the WHO-recommended value of 21ºC. Correspondingly, for periods of likely occupation, average bedroom temperatures appear to have increased. Compared with non-domestic buildings, there have been fewer investigations of domestic thermal comfort, either in the UK or elsewhere, and hence the paper also calls for further detailed investigations of domestic indoor temperatures during occupied hours together with thermal comfort evaluations in order to better understand domestic thermal environments. Based on suggestions from the limited range of studies available to date, living room temperatures may need to be maintained within the range 20-2 22 ºC for thermal satisfaction, though this requires confirmation through further research. The study also emphasises that improving the energy efficiency of homes should be the primary means to effect any increases in indoor temperatures that are deemed essential. Considerations for future policy are discussed.

Keywords

UK solid wall dwellings, Indoor temperatures, Domestic thermal comfort

1 Introduction

Within the UK, energy used in homes accounts for more than 25% of total national energy consumption. Up to two thirds of the energy used in homes is for the purposes of space and water heating, with the attainment of occupant thermal comfort therefore having a direct bearing on energy demand. The UK Government is embarking upon a large scale program of refurbishment for its housing stock, financially supported by the 'Green Deal', with the aim of improving the energy efficiency of existing homes through improvement in space and water heating systems and reductions in whole house heat loss. However, there is a risk that

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much of the anticipated energy savings may not be realized in practice as people may choose to maintain their homes at temperatures higher than those before refurbishment. Studies have shown that actual savings from the energy efficient retrofitting of existing houses have amounted to less than half of the predicted savings for a variety of reasons that include quality and detailing of the refurbishment process as well as the 'takeback' process - the latter initiated due to improvements in thermal comfort (Hong *et al.* 2006). The 'take-back' (a result of improved thermal comfort and consequently reduced clothing level) was also observed in another study where an increase of whole house neutral temperature from 18.9°C to 19.1°C was recorded after the installation of energy efficiency measures (Hong *et al.* 2009). Therefore, an in-depth understanding of indoor thermal conditions and people's domestic thermal comfort is required so that energy efficiency upgrades are delivered, and anticipated energy savings are achieved, whilst also fulfilling people's thermal comfort needs. Currently there is limited knowledge on domestic thermal comfort in the UK, and a number of questions arise - for example, at what temperatures are people actually living in their homes? Are people thermally satisfied with the temperatures in their homes? Are people living in temperatures close to the World Health Organisation (WHO) - recommended values of 21°C in living rooms and 18°C in bedrooms? There appears to be a generally-held belief that UK domestic indoor temperatures have been increasing over the last few decades, but is this actually the case? This paper provides some answers, clarifications and insights that help towards addressing these questions. This is achieved by conducting a historical review and synthesis of measured data on temperatures in UK homes since 1969, together with an analysis of the temperature data that were recorded in solid-walled homes in the East Midlands area as part of the CALEBRE[1] research project.

2 A review of measured UK domestic temperatures

A review of indoor temperatures recorded in surveys of UK homes from 1969 is given in this section and is largely focused on heating season (winter and spring) temperatures. An increased awareness of the health risks to the elderly as a result of living in low indoor temperatures in cold environments led to studies of indoor temperatures in homes during the 1960s and 1970s. A survey conducted in February 1969 of 144 homes (a mix of modern flats and substandard homes) occupied by elderly people found that living room and

bedroom temperatures were in the range of 3-14°C in substandard houses while in modern flats they were in the range of 9-17°C (Collins, 1986). One of the first large scale surveys of indoor temperatures was carried out in the winter of 1972 and covered a sample of 1020 elderly people (aged 65 and over) living in 100 constituencies across Great Britain, including the London Borough of Camden (Fox *et al*. 1973). Average living room temperatures of 16.2°C and 18.2°C were recorded in homes across the UK and in Camden, respectively. The study found that in the majority of the cases (75%), living room temperatures were below 18.3°C. This was close to the minimum level of 18°C that had been recommended by the Parker Morris report of 1961 (Ministry of Housing and Local Government, 1961) as a heating standard for living areas (but not bedrooms) when the external temperature was -1°C. The purpose of the Parker Morris report of 1961 had been to consider standards of design and equipment for family dwellings and other forms of residential accommodation. The report also identified that better heating was a key design factor, with homes at the time being recognised as too cold for daytime and evening use, except in summer. This came alongside an increasing demand for higher domestic comfort levels to match expectations acquired from conditions in offices and factories. A repeat study of 47 elderly residents in the London Borough of Camden was subsequently conducted in 1975-6. The study recorded a mean living room temperature of 18.4°C during afternoons (Collins *et al*. 1977).

To investigate at what temperatures people were living in their homes, a large scale survey was carried out by The Building Research Establishment in 1978 (Hunt & Gidman, 1982). The survey took spot measurements of temperatures in each room of the randomly selected 1000 dwellings. The dwellings were a mix of owner occupied and local authority rented properties and were located in 50 towns across England, Scotland and Wales. Measurements were taken during mornings, afternoons and evenings, and on weekdays as well as weekends. An average living room temperature of 18.3°C, and an average bedroom temperature of 14.6°C, was recorded across the sample.

In order to understand the impact of insulation levels and occupant preferences on internal temperatures, a field study of 33 houses (almost equal numbers of un-insulated and retrofit insulated homes) and newly-built, well-insulated homes was conducted in 1977/78 by the Watson House Research Centre of the British Gas Corporation (Nevrala & Pimbert, 1981).

Temperatures in living rooms and bedrooms were continuously recorded throughout the monitoring period. The survey recorded an average internal temperature of 19.8°C in uninsulated homes, 20.3°C in retrofit-insulated homes and 21.6°C in new-built insulated homes during evenings, with 90% of the respondents voting these temperatures as satisfactory. Four participants of this study had also taken part in another study of subjective responses to temperatures in office environments. Comparison of both studies highlighted that average evening living room temperatures in these participants' homes (which were reported as satisfactory) were 3°C lower than the long term preferred temperature at the office. The study suggested that the increased tolerance toward lower temperatures at home could be as a result of people having to pay for their domestic fuel themselves (as opposed to their employer paying the fuel bill).

A survey of internal temperatures in new homes was conducted by Oseland in winter and summer of 1991/92 with the aim of investigating differences between reported and predicted neutral temperatures in homes as well as seasonal differences in neutral temperatures (Oseland, 1994). An average living room temperature of 19.3°C was recorded in winter in 515 homes, whilst in summer an average living room temperature of 21.7°C was recorded in 293 homes. The study observed that the neutral temperature was lower (5°C lower in winter and 3°C lower in summer) than those predicted using the Standard ISO 7730 (BSI, 2005). The study also observed that the participants rated themselves warmer in winter than in summer, even though living room temperatures were lower during the winter period.

The comprehensive English House Condition Survey (EHCS) in 1986 recorded temperatures of 18°C in the living rooms of 2177 homes across the UK (DOE, 1995). The 1991 EHCS recorded an average living room temperature of 18.6°C in a total of 25,000 centrally heated and non-centrally heated homes. Spot measurements of temperatures were taken during interviews (DOE, 1996), thus implying that the recorded temperatures were representative of values that prevailed during occupancy. The 1996 EHCS recorded average living room temperatures of 18.1°C (DETR, 2000). Temperature measurements were discontinued after the EHCS of 1996 and currently there are no comprehensive data available from the EHCS on internal temperatures in UK dwellings for the period after 1996.

A handful of surveys on indoor air temperature in dwellings have been carried out since 1996, but they were conducted primarily in fuel poor and low income households. The Warm Front Study Group recorded winter indoor temperatures in low income households in the UK and observed a median standardized daytime living room temperature of 19.1°C and a median standardized night time bedroom temperature of 17.1°C (Oreszczyn *et al*. 2006). Extrapolating detailed temperature data from a subset of 1600 dwellings, the study observed that dwellings that received both heating and insulation measures through the Warm Front scheme had daytime living room temperatures 1.6°C higher and night time bedroom temperatures 2.8°C higher than pre-intervention dwellings. Furthermore, actual energy savings were lower than the theoretically-predicted energy savings, suggesting a 'takeback' effect. 'Takeback' is a comfort-related phenomenon, and is defined as *'a shortfall in actual energy savings in practice as a result of an increase in the average indoor temperature of the houses, following an energy efficiency upgrade, due to the physical processes involved and because the occupants deliberately take back some of the potential energy savings as improved comfort'* (Milne & Boardman, 2000).

The CaRB project conducted a follow-up study of 15 'low-energy' dwellings in Milton Keynes, UK (Summerfield *et al*. 2007). Temperature was continuously monitored during 2005-2006 and was compared with monitoring carried out in 1989-1991 to determine changes in internal temperatures and energy use. Results indicated no significant change in average internal temperatures over the 15 years under standardised daily outdoor conditions (5°C). An average temperature of 20.1°C (0.2°C higher than 1990) was recorded in living rooms, with 19.3°C (0.4°C lower than 1990) being recorded in main bedrooms. The study did, however, find an increase of up to 20-30% in energy consumption in these houses. The study noted that energy consumption may not necessarily stabilise and may even increase even if internal temperatures stabilise or decline in future.

Yohanis and Mondol conducted a survey of the internal temperatures of 25 households in Northern Ireland in 2007 (Yohanis & Mondol, 2010). The survey, conducted from February 2004 to January 2005, recorded daily average temperatures of 15.6°C to 21.7°C in living rooms, and 16.1°C to 20.5°C in bedrooms in the winter. During summer, the survey recorded daily average temperatures of 20.1°C to 22.2°C in living rooms, and daily average

temperatures of 20°C to 22.2°C in bedrooms. Overall, the survey recorded an average temperature of 20.5°C in living rooms and 19.9°C in bedrooms.

The 'Challenge 100' project carried out by E.ON, the energy utility company, monitored living room and bedroom temperatures in homes located in the Birmingham (Midlands) area of the UK during 2010 (E.ON, 2010). These homes were occupied by households who were identified as being 'fuel poor'. At the time of the study, the prevailing definition was that a household is said to be in fuel poverty if it needs to spend more than 10% of its income on fuel to maintain a satisfactory heating regime (usually 21°C for the main living area, and 18°C for other occupied rooms) (DECC, 2011). The aim of the Challenge 100 project was to eradicate fuel poverty for 100 families, in 100 homes, in 100 days. Therefore, energy efficiency upgrades were carried out for these houses, and temperatures were monitored after the refurbishment. An average temperature of 19.2°C in living rooms and 19.3°C in bedrooms was recorded. The review of measured UK domestic temperatures presented above, together with further recent data to be presented in the next section, is discussed later in section 4 of this paper.

3 Current temperatures in UK homes – the CALEBRE sample

3.1 Background to the CALEBRE study

According to the English House Conditions Survey 2006, solid-walled dwellings (6.6 million) constitute approximately 31% of the total UK housing stock. With a view to understanding at what temperatures people were living in their solid-walled homes, the CALEBRE research project undertook monitoring of living room and bedroom temperatures in 20 solid-walled, owner-occupied homes (housing a total of 66 residents) in and around the town of Loughborough (East Midlands, UK). The monitoring was carried out from February 2010 to May 2010. The EHCS database was used to understand the national profile of the solid wall housing stock and to identify a sample of houses for investigation that would provide a representative cross-section of different domestic situations. Participants were selected using a purposive sampling approach such that they not only lived in a wide range of house types, but also represented a variety of family structures, incomes and social statuses. Comparison of the CALEBRE sample with the EHCS data is given in Table 1.

Table 1. Comparison of the 'CALEBRE' sample with the EHCS national profile of solid wall dwellings

| Criterion	EHCS	'CALEBRE' sample
Dwelling Type	70% of the solid wall housing stock consists of end terrace, mid terrace, semi-detached and detached property types	Equal numbers (5 of each) of end, mid, semi and detached properties
Dwelling Size	85% of solid wall properties have an area of more than 50sqm, the remaining 15% (being less than 50sqm) comprising 1-2 bedroom properties.	All CALEBRE properties had an area of more than 50sqm
Regional Locations (Government office regions)	30% of the total solid wall housing stock is in London, while less than 3% are in the north east, the rest being located evenly in other regions	All properties located in East Midlands
Regional Location (urban/rural)	75% of the total solid wall housing stock is located in urban centres (not city centres) and suburban residential regions	75% of CALEBRE properties (n=15) in urban centres and suburban residential regions. Remaining properties: 10% village centre, 5% city centre, 5% rural residential, 5% rural
Type of Tenure	80% of the total solid wall housing stock is owner occupied and privately rented occupied	All owner occupied
Type of Fuel Used	85% of solid wall dwellings use gas for heating.	All gas central heating
Household Composition	Solid wall properties have an even mix of household composition that includes couples less than 60 years of age with and without dependent children, couples above the age of 60 years with no dependent children, multi person households and lone parents.	55% of CALEBRE households were couples aged less than 60 years with dependent children; 15% multi person households; 10% couples under 60 years with no dependent children; 10% lone person over 60 years; 5% couples less than 60 years without dependent children; 5% lone person less than 60 years
Household Size	90% of solid wall properties have a household size in the range of 1 to 4 occupants with less than 10% having an occupancy greater than 4	85% of CALEBRE properties had a household size in the range of 1 and 4 occupants, with 15% having an occupancy greater than 4

For the first sample of 9 houses (10 living rooms, 6 bedrooms), temperatures were recorded at hourly intervals from February 2010 to April 2010. Data for the period 11th February to 24th February 2010 were analysed and are presented in this study. This period is referred to as the 'winter study period'. For the remaining sample of 11 houses (10 living rooms and 11 bedrooms), temperatures were recorded at hourly intervals from April 2010 to May 2010. Data for the period 01st April to 14th April 2010 were analysed and are presented in this study and referred to as the 'spring study period'. Temperatures were recorded using HOBO temperature sensors (accuracy ± 0.35°C from 0° to 50°C) placed at approximately 1.5m height above floor level, ensuring that they were not hidden behind or under furniture, and also ensuring that they were not exposed to direct sunlight or any other heat source.

3.2   Analysis of CALEBRE data collected

Summary statistics of the outdoor and indoor living room and bedroom temperatures recorded during the winter and spring study periods are given in Table 2. Outdoor temperature was recorded by the local weather station operated by the Department of Geography at Loughborough University. No house in the sample was more than 15 miles from this weather station. Average outdoor temperatures of 2.4°C and 8.4°C were recorded during the winter study period and spring study period, respectively. As shown in Table 2, a wide range of indoor temperatures, ranging from a minimum of 10.9°C to a maximum of 25.9°C were recorded during both study periods. However during the hours of evenings (18:00 to 24:00), average living room temperatures were 18.7°C (SD= ±1.6°C) and 18.4°C (SD= ±2.5°C) for winter and spring study periods, respectively. Average of bedroom temperatures during the night (00:00 to 06:00) was 17.2°C (SD= ±1.5°C) and 17.4°C (SD= ±2.5°C) for winter and spring study periods, respectively. These time periods were selected as being those when living rooms and bedrooms were most likely to have been occupied. Hourly average, maximum and minimum temperatures2 recorded in living rooms during evenings (18:00 to 24:00) and in bedrooms during nights (00:00 to 06:00) together with outdoor temperatures for the winter study period (11-24 February 2010) and the spring study period (01-14 April 2010) are compared with the WHO recommended temperatures (Ranson, 1988) in Figure 1, Figure 2, Figure 3 and Figure 4. As shown in these figures, average hourly living room and bedroom temperatures were lower than the WHO recommended values of 21°C for living rooms and 18°C for bedrooms.

Table 2. Statistics of outdoor and indoor living room and bedroom temperatures recorded at hourly intervals during the winter study period (11-24 February 2010) and spring study period (01-14 April 2010) in solid wall houses near Loughborough, East Midlands, UK

|	Average (°C)	Maximum (°C)	Minimum (°C)
Winter Study Period			
Outdoor temperature	2.4	11.2	-2.7
Living room temperatures (00:00 to 24:00hrs) (n=10)	17.8	25.9	10.9
Living room temperatures (evenings,18:00 to 24:00 hrs) (n=10)	18.7	23.2	12.3
Bedroom temperatures (00:00 to 24:00 hrs) (n=06)	17.6	23.6	11.3
Bedroom temperatures- night time (00:00 to 06:00 hrs) (n=06)	17.2	20.7	11.6
Spring Study Period			
Outdoor temperature	8.4	17.8	1.3
Living room temperatures (00:00 to 24:00 hrs) (n=10)	17.5	25.1	11.6
Living room temperatures (evenings,18:00 to 24:00 hrs) (n=10)	18.4	24.7	12.0
Bedroom temperatures (00:00 to 24:00 hrs) (n=11)	18.0	22.9	10.3
Bedroom temperatures- night time (00:00 to 06:00 hrs) (n=11)	17.4	22.8	10.4
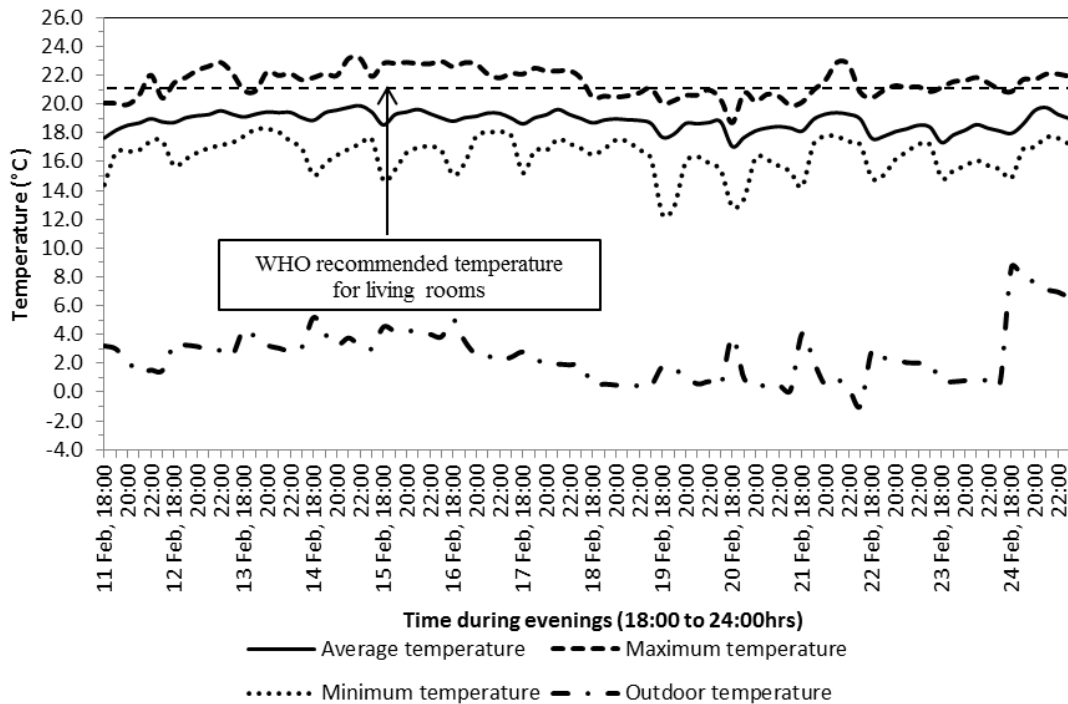
Figure 1. Hourly living room temperatures recorded during evenings (18:00 to 24:00hrs, 11-24 February 2010) in solid wall houses near Loughborough, East Midlands, UK, compared with the WHO recommended temperature (winter study period)
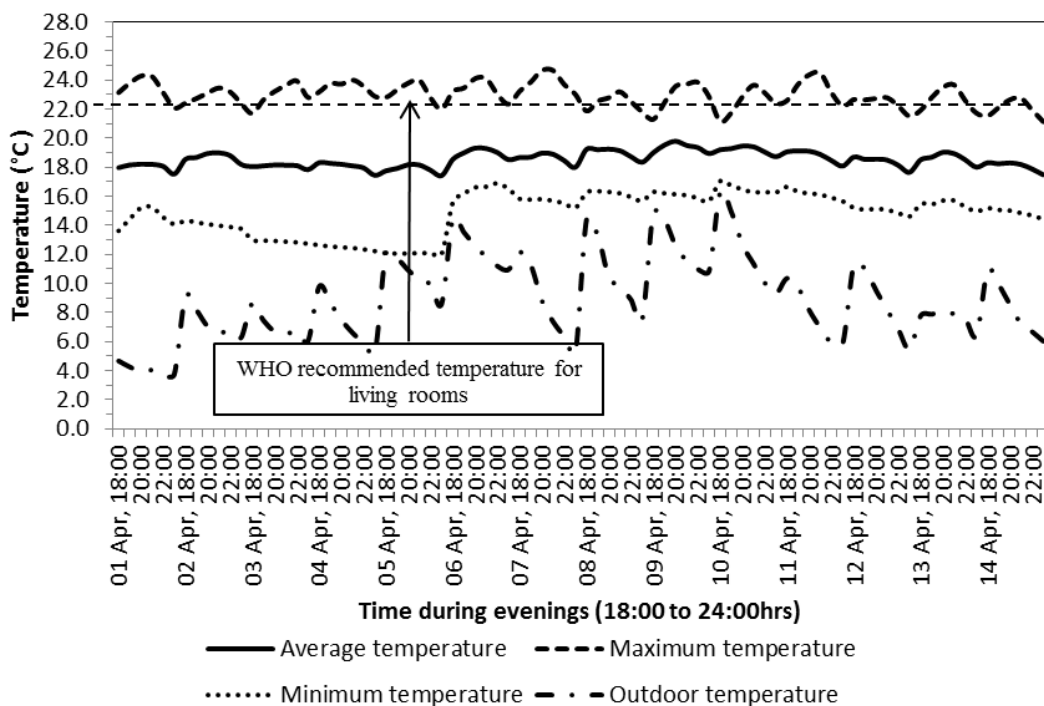
Figure 2. Hourly living room temperatures recorded during evenings (18:00 to 24:00hrs, 01-14 April 2010) in solid wall houses near Loughborough, East Midlands, UK, compared with the WHO recommended temperature (spring study period)

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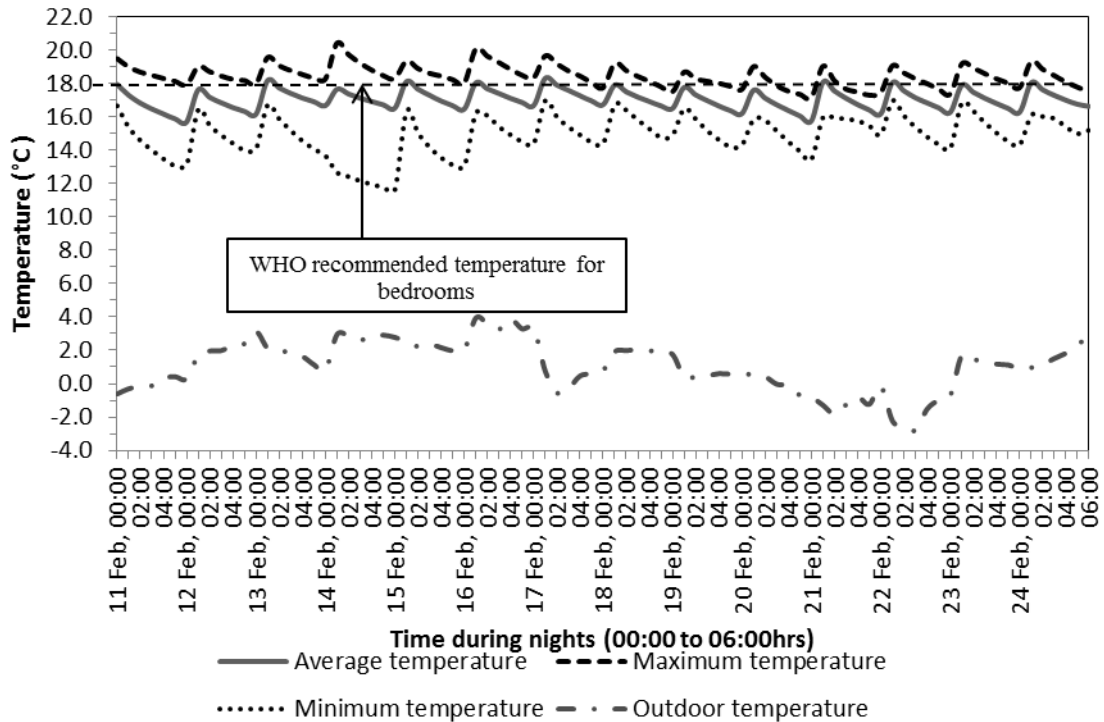
Figure 3. Hourly bedroom temperatures recorded during nights (00:00 to 06:00hrs, 11-24 February 2010) in solid wall houses near Loughborough, East Midlands, UK, compared with the WHO recommended temperature (winter study period)
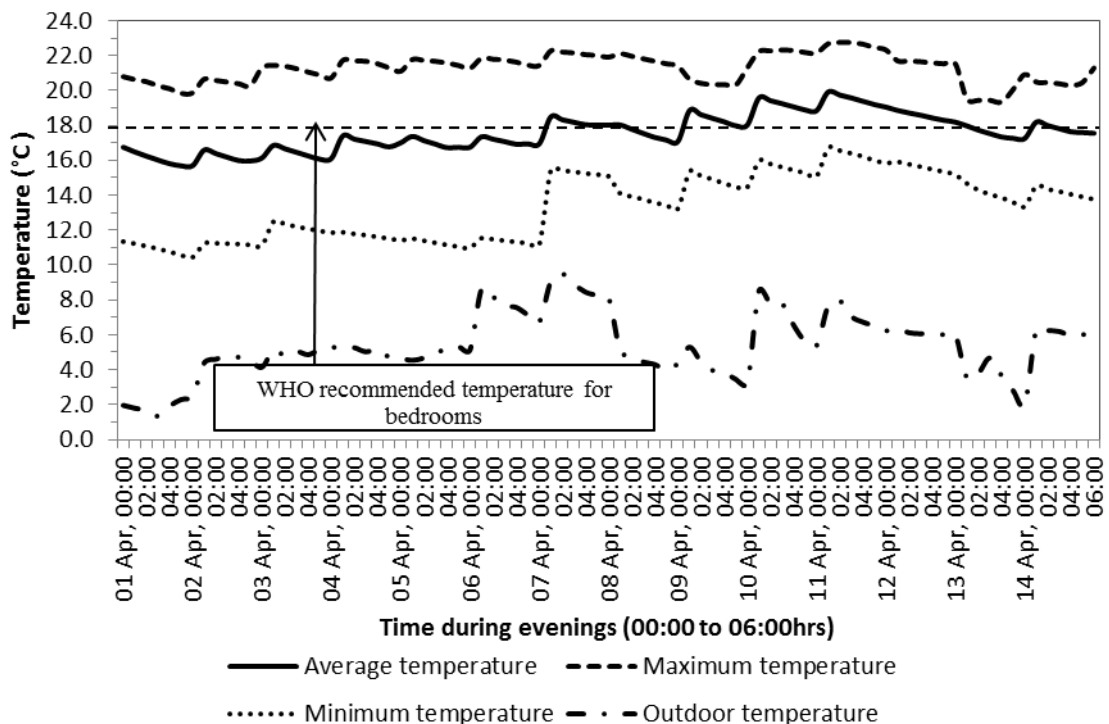
Figure 4. Hourly bedroom temperatures recorded during nights (00:00 to 06:00hrs, 01-14 April 2010) in solid wall houses near Loughborough, East Midlands, UK, compared with the WHO recommended temperature (spring study period)

3.3 Percentage distribution of temperatures

The percentage distribution of living room temperatures recorded during evenings (18:00 to 24:00hrs) and bedroom temperatures recorded during nights (00:00 to 06:00hrs) are shown in Figure 5. In living rooms, 93% of temperatures recorded during the winter study period and 84% of temperatures recorded during the spring study period were below the WHO-recommended value of 21°C. In bedrooms, 68% of temperatures recorded during the winter study period and 53% of temperatures recorded during the spring study period were below the WHO-recommended value of 18°C. A small proportion of temperatures were above the recommended values. In living rooms, 7% of temperatures recorded during the winter study period and 14% of temperatures recorded during the spring study period were above 21°C. In bedrooms, 8% of temperatures recorded during the spring study period were above 18°C, although none of the winter study temperatures were above 18°C. These findings show that for the solid-walled houses investigated, a significant proportion of the temperatures recorded during periods of likely occupancy were below the WHO recommended values of 21°C and 18°C suggesting that, either the householders choose to live at lower temperatures, or that these houses were not able to achieve and maintain the recommended temperatures.
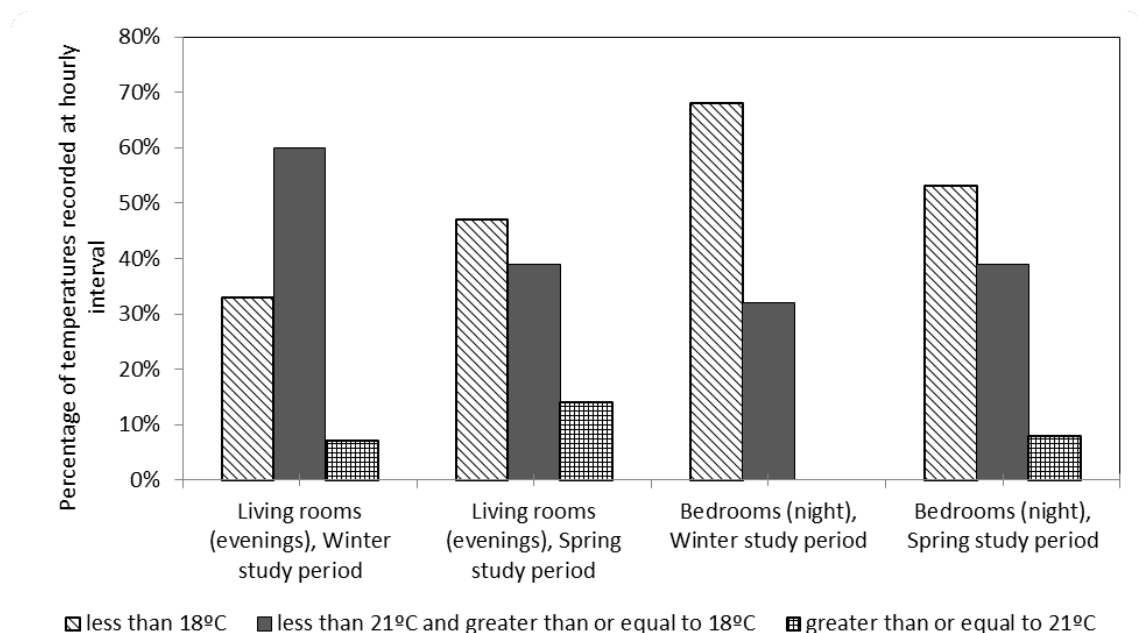
Figure 5. Percentage distribution of temperatures in living rooms (evenings, 18:00 to 24:00) and bedrooms (nights, 00:00 to 06:00)

3.4   Temperature variations according to time of day

As shown in Figure 6 and Figure 7, during both study periods, average temperatures were lowest during nights (00:00-06:00) and mornings (06:00-09:00), gradually increased during the day time, and peaked during evenings suggesting operation of space heating during occupation. A high proportion of the CALEBRE houses had someone who was often at home in the day; almost half of the sample (45%) fell into this category.
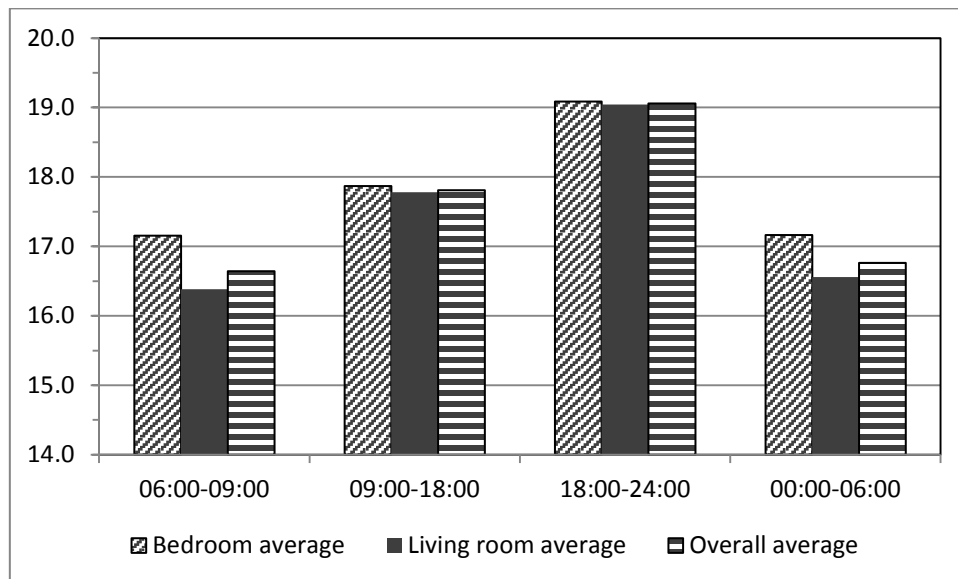

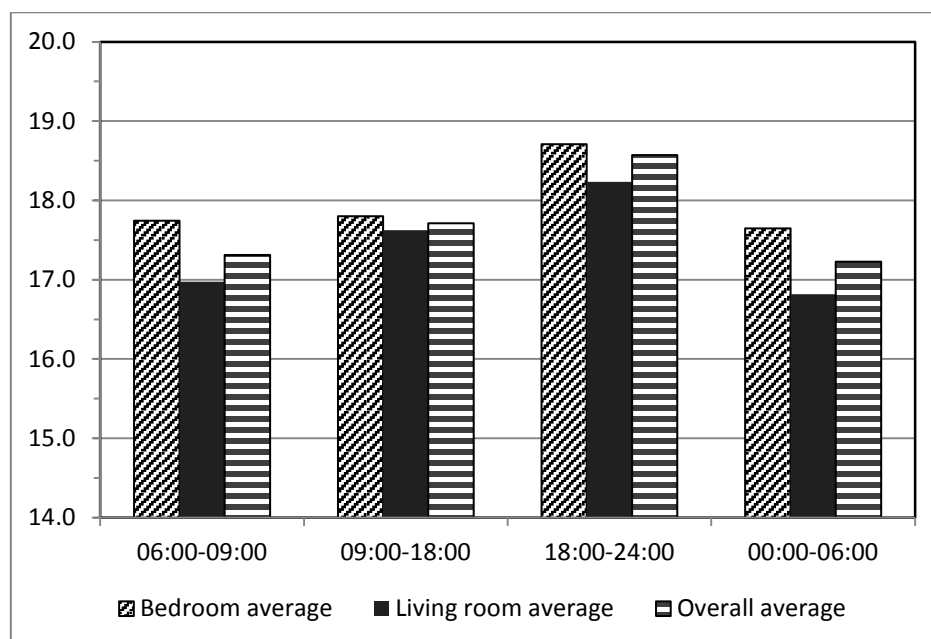**Figure 6. Average temperatures during time of day (winter study period)**

Figure 7. Average temperatures during time of day (spring study period)

The above data gathered during 2010 on solid-walled dwellings in Loughborough, as part of the CALEBRE project, were added to those from the historical review and are discussed later (in section 4).

3.5   Reported thermal comfort

In addition to the quantitative temperature data collected in the CALEBRE sample, qualitative data were also gathered on thermal comfort sensations. Whilst this part of the study was not a full thermal comfort survey, nevertheless householders in the properties were asked to report times when they felt their thermal environment was uncomfortable. They were given a simple diary sheet to complete, identifying which member of the household was reporting the discomfort, the day, time and location in the house and in particular what they might have done to alleviate the discomfort. Data were collected over a period of several weeks in some cases, although not all instances of discomfort were noted. This information provides an insight into whether the temperatures measured in these homes were acceptable or not to their occupants. Any reported adaptive behaviours could suggest some dissatisfaction with the temperature, and that householders wanted some alternative conditions.

A total of 185 records gathered from 18 of the 20 households were analysed to determine the cause of any reported discomfort. Occupants were asked to report discomfort against the following categories: too hot, too cold, too draughty, too stuffy, too damp and too dry.

The suggested reasons for the discomfort and the action taken to alleviate it were also categorised. A total of 66% (n=123) of the diary records indicated that a householder felt that the local environment was too cold at a particular time, almost 22% (n=40) records showed it was too hot, almost 8% (n=14) too draughty and of the remainder: 2% too damp, 2% too stuffy and 1% too dry. The fact that the majority of records from householders stated that they were too cold suggests that the internal temperatures were generally lower than people wanted, the reasons for which require further consideration. It is possible that the homes were too cold because the householders were not able to heat their homes to a higher temperature (perhaps because of an inefficient heating system or as a result of heat

losses) or because they chose not to heat their homes sufficiently. Explanations given by the householders for why the room or house was too cold are shown in Table 3.

Table 3. Reported reasons for being too cold

Reason for being too cold	Number of records	Percentage of total too cold (n=123)
Heating not on	45	37%
Inadequate heating in the room	22	18%
Inactivity - Sitting still	11	9%
Particularly cold night or day	10	8%
Draught of cold from another room	9	7%
Heating had gone off	7	6%
Heating was turned down	5	4%
Just come in from a warmer room	3	2%
Heating only just come on	3	2%
Insufficient clothes on	3	2%
Heating not working properly	2	2%

These results show that the main reason reported for a householder being too cold was that the heating was not turned on in their house or the room in which they were located. In some cases, this was because the heating was programmed to come on at a later time. In other cases, the householder did not use their central heating system and instead switched on a local heater once they entered a particular room. Examples of comments included the following:

- *'Got up early, the heating is not on properly yet'* (Female, 6:15 am)
- *'Heating not on at that time'* (Male, 10:30pm)
- *'Been out, the house was cold'* (Male, 4:00pm)

In some cases, the heating was on in the room, but the temperature was not sufficiently high:

- *'Cold outside and heating not up too high'* (Female, 5.40pm)
- *'Checked and found the thermostat had been turned to 19 (°C), not enough!'* (Female, 7:45pm)

The cases where the heating was not working properly related to temporary faults rather than poor efficiency. The action taken by householders in response to these cold conditions

showed interesting results, as shown in Table 4. In many cases, householders did more than one thing in order to feel warmer, so total percentages add up to more than 100%.

Table 4. Reported adaptive behaviours taken by householders

Adaptive behaviour taken	Number of records	Percentage of total too cold (n=123)
Put on more clothing	42	34%
Put on a local heater	30	24%
Turn up the heating	22	18%
Turn on the heating	18	15%
Use a blanket or throw	12	10%
Shut doors	9	7%
Nothing	5	4%
Move nearer the heat source	4	3%
Be more active	2	2%
Move to a location somewhere warmer	3	2%
Eat some hot food or drink	3	2%
Close the window	1	1%
Close the curtains	1	1%
Take a hot bath	1	1%
Go to bed	1	1%

4 Discussion

4.1   A comparison of measured and recommended temperatures in homes

In this final part of the paper, we return to the data reviewed in Section 2 supplemented by that of the CALEBRE study described in Section 3, synthesise and present these data graphically, and then discuss the findings and potential implications. The World Health Organisation (WHO) conducted a review of evidence from scientific and epidemiological European studies that investigated adverse effects on health of low indoor temperatures, particularly in high-risk groups. In 'Guidelines for healthy housing' (Ranson, 1988) the WHO recommended minimum domestic temperatures of 21°C for living rooms and 18°C for bedrooms. In addition to the WHO, the British Standards (BSI, 2005) specify a temperature range of 18-21°C in winter for dwellings that have mechanical heating and cooling. The CIBSE Guide A (CIBSE, 2011) recommends a temperature range of 20-22°C for living rooms and 17-19°C for bedrooms in winter. Temperatures of 21°C in living rooms and 18°C in bedrooms are also considered to be in the comfort range by the UK Government (DEFRA,

2008) , and are currently being used by the software RdSAP to calculate a dwelling's energy efficiency (DECC, 2009).

Average living room and average bedroom temperatures measured over the period 1969 to 2010 and relating largely to occupied periods3 (unless otherwise stated) in winter and spring time have been plotted and are shown in Figure 8, where they are compared with WHO-recommended temperatures. Table 5 accompanies Figure 8, and presents summary statistics (not exhaustive) to provide some measure of dispersion relating to the points in Figure 8. Inspection suggests that many winter and spring-time living room temperatures measured during largely-occupied periods have been historically lower than the WHO recommended temperature of 21ºC.The CALEBRE study recorded average living room temperatures of 18.7ºC in solid-walled dwellings, with a significant proportion of temperatures lower than the WHO-recommended value.

There have been a limited number of studies conducted of bedroom temperatures. Inspection of available data in Figure 8 together with their corresponding statistics in Table 5 suggest that many of the measured bedroom temperatures before the 1980s have been lower than the WHO-recommended value of 18 ºC, having increased after the 1980s, to remain mostly in the range of 18 to 21ºC. The CALEBRE study recorded an average bedroom temperature of 18.1 ºC.
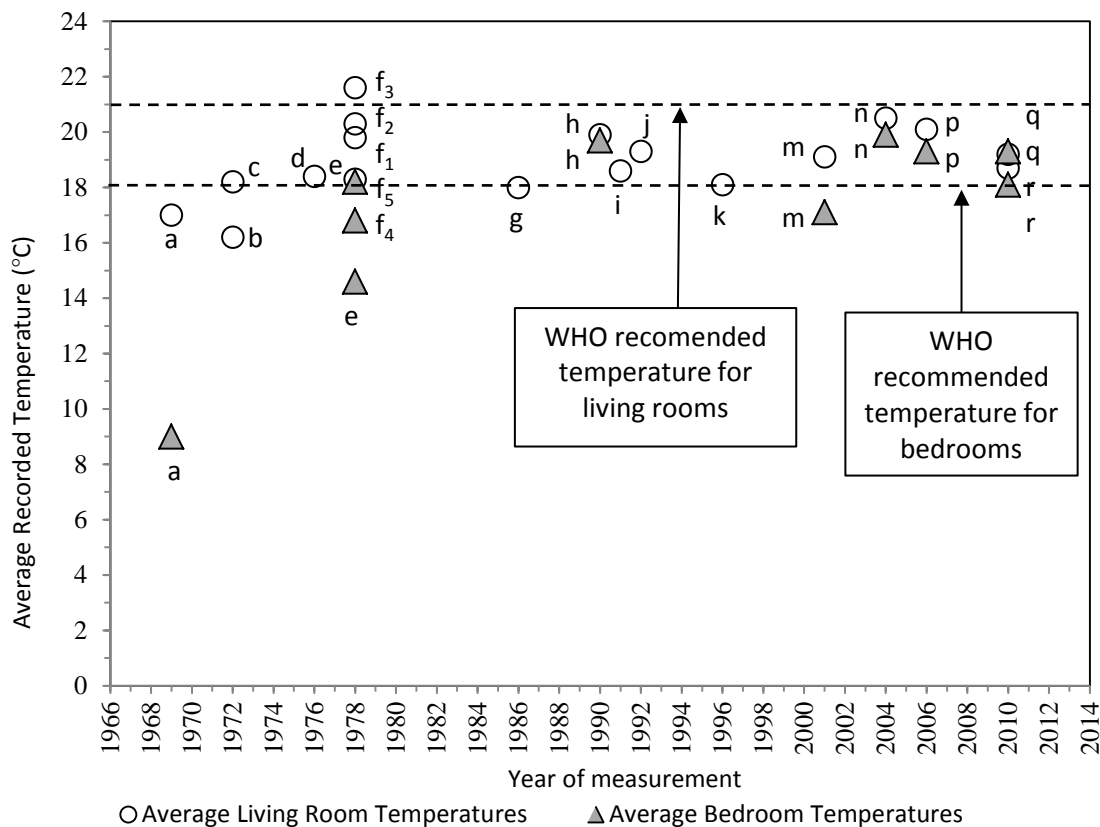
Figure 8. Trend of average internal temperatures recorded largely during occupied periods (unless otherwise stated) in UK dwellings from 1969 to 2010

a. Modern flats [n = 72], elderly residents, located in Birmingham, 1969, occupied (Collins, 1986).
b. Various house types, elderly residents [n = 973], spread across the UK, 1972, occupied (Fox *et al*. 1973).
c. Various house types, elderly residents [n = 47], located in London Borough of Camden, 1972, occupied (Fox *et al*. 1973).
d. Same house and residents as in 'c', 1975-6, occupied (Collins *et al*. 1977).
e. Various house types, various types of residents [n = 1000], spread across the UK, 1978, occupied (Hunt & Gidman, 1982).
f_1. Uninsulated homes [n = 15], various types of residents, 1977-1978, occupied (Nevrala & Pimbert, 1981).
f_2. Retrofit insulated homes [n = 16], various types of residents, 1977-1978, occupied (Nevrala & Pimbert, 1981).
f_3. New-built well insulated homes [n = 7], various types of residents, 1977-1978, occupied (Nevrala & Pimbert, 1981).
f_4. Uninsulated homes [n = 15], various types of residents, 1977-1978, very likely occupied (Nevrala & Pimbert, 1981).
f_5. Retrofit insulated homes [n = 16], various types of residents, 1977-1978, very likely occupied (Nevrala & Pimbert, 1981).
g. Various house types [n = 2177], various types of residents, spread across the UK, 1986, occupied (DOE, 1995).
h. Low energy home [n = 14], various types of residents [n = 38], located in Milton Keynes, 1989-91, occupancy may vary (Summerfield *et al*. 2007).
i. Various house types [n = 25000], various types of residents, spread across the UK, 1991, occupied (DOE, 1996).
j. Owner-occupied homes [n = 860] of similar size and design, with cavity and loft insulation, double glazing, built during 1998-1990 by only 2-3 different building companies, various types of residents, spread across the UK, 1991-92, occupied (Oseland, 1994).
k. Various house types [n = Unknown.], various types of residents, spread across the UK, 1996, occupied (DETR, 2000).
m. Various house types [n = 1600], various types of residents, spread across the UK, 2005-06, occupancy may vary (Oreszczyn *et al*. 2006).
n. Various house types [n = 25], various types of residents, spread across the Northern Ireland, 2007, occupancy may vary (Yohanis & Mondol, 2010).
p. Same houses and residents as in 'h', 2006, occupancy may vary (Summerfield *et al*. 2007).
q. Various house types [n = 12], various types of residents, spread across the Midlands, 2009-10, occupancy may vary (E.ON, 2010).
r. Solid wall house [n = 20], various types of residents (owners) [n = 56], located in and around Loughborough, 2009-10, very likely occupied.

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Table 1. Summary statistics (not exhaustive) relating to the points shown in Figure 8, gathered from the papers reviewed

Year of study & Point in Fig.8	Average Living Room Temp, °C	Std Dev (Living Room), °C	Max. Living Room Temp, °C	Min. Living Room Temp, °C	Average Bedroom Temp, °C	Std Dev (Bedroom), °C	Max. Bedroom Temp, °C	Min. Bedroom Temp, °C	Publication
1969 a	17	NR	NR	NR	9	NR	NR	NR	Department of Social medicine, Birmingham University,
1972 b	16.2	3.27	NR	NR	NR	NR	NR	NR	Fox *et al* (1973)
1972 c	18.2	3.15	NR	NR	NR	NR	NR	NR	Fox *et al* (1973) and Collins *et al* (1977)
1976 d	18.4	2.69	NR	NR	NR	NR	NR	NR	Collins *et al* (1977)
1978 e	18.3	3	NR	NR	14.6	3.3	NR	NR	Hunt and Gidman (1982)
1981 f_1 & f_4	19.8	NR	25	16	16.8[+]	NR	24[x]	10[x]	Nevrala and Pimbert (1981)
1981 f_2 & f_5	20.3	NR	26	16	18.2[+]	NR	24[x]	10[x]	Nevrala and Pimbert (1981)
1981 f_3	21.6	NR	26	16	NR	NR	NR	NR	Nevrala and Pimbert (1981)
1986 g	18	3.1	27.3	4.5	NR	NR	NR	NR	EHCS (1986)
1990 h	19.9[+]	NR	20[**]	19.8[**]	19.7[+]	NR	19.8[**]	19.6[**]	Summerfield *et al* (2007)
1991 i	18.6	NR	NR	NR	NR	NR	NR	NR	EHCS (1991)
1992 j	19.2[xx]	2.2	NR	NR	NR	NR	NR	NR	Oseland (1994)
1996 k	18.1	NR	NR	NR	NR	NR	NR	NR	EHCS (1996)
2001 m	19.1[++]	NR	23[*]	13.5[*]	17.1[++]	NR	21.8[*]	12.1[*]	Oreszczyn *et al* (2006)
2004 n	20.5	NR	23.9[#]	16[#]	19.9	NR	23.9[#]	16[#]	Yohanis and Mondoll (2010)
2006 p	20.1[+]	NR	20.3[**]	19.8[**]	19.3[+]	NR	19.6[**]	19.1[**]	Summerfield *et al* (2007)
2010 q	19.2	2.9	26.9	14.7	19.3	2.8	27.1	11.8	Challenge 100
2010 r	18.7	2.3	25.9	12.0	18.1	2.2	23.6	10.7	CALEBRE

NR = not reported, not available or not applicable

* = (5th percentile) and (95th percentile) reported

** = 95% confidence interval reported

[+] = for, or standardized to, an external temperature of +5°C

[++] = median values, for standardized external temperature of +5°C

[x] = for a mean diurnal (external) temperature between -2°C and 0°C

[xx] = for a mean outdoor temperature of 12.1°C

[#] = for more than 85% of bedrooms and 90% of living rooms

4.2   Have domestic indoor temperatures risen over the last 40 years?

There exists a popular belief that temperatures in UK homes have risen over the last few decades, but to what extent is this actually the case? Work by Utley and Shorrock (2008) suggests that indoor domestic temperatures have risen. However, their reference is to that of an increase in whole house temperatures, with estimates of temperature rise being predominantly based on modelling work together with findings from a limited selection of measured data. Our synthesis and presentation in Figure 8 of a large selection of measured data shows a generally horizontal trend, suggesting that there has been little or no increase in winter and spring-time average living room temperatures measured during largely occupied periods over the last 40 years.

However, bedroom winter and spring-time average temperatures measured during largely occupied periods do appear to have increased over the last 40 years, though this is based only on the limited data available. Any increase in average bedroom temperatures would, however, be consistent with the historical growth of domestic central heating installations, as well as reduction in whole house heat loss. It has been noted (Utley & Shorrock, 2008) that central heating ownership has increased from 30% in 1969 to 55% in 1979 and to 75% in 1990. Considering average living room and average bedroom temperatures together, there would have been a slight increase in whole house temperature, consistent with the preceding discussion. Shipworth *et al*. (2010) found no statistical evidence for changes in reported thermostat settings in English homes between 1984 and 2007, suggesting that the extent of dwelling area heated, amongst other things, might explain why domestic heating energy use has not declined despite efficiency improvements. The lack of change in reported thermostat setting would be in accord with the findings we present in this paper.

4.3   Indoor domestic thermal comfort

Compared with thermal comfort investigations in commercial and office environments, there have been relatively fewer studies on domestic thermal comfort, either in the UK or elsewhere. For the UK, Oseland's study (Oseland, 1994) concluded that reported neutral temperatures were lower than those predicted by ISO7730 (BSI, 2005). A further study by Oseland (1995) found a context effect, namely that reported neutral temperatures in homes were lower than those in offices and climate chambers, for the same set of subjects. The

paper suggested that adaptive actions in the domestic context could have been responsible for these differences.

Oreszczyn *et al*. (2006) reported on the effects of domestic energy efficiency measures taken under England's 'Warm Front' programme, observing that these led to substantial improvements of both living room and bedroom temperatures and that these are likely to have benefits in terms of thermal comfort. This was reported in more detail by Hong *et al*. (2009), who described surveys that were carried out in Warm Front households before and after energy efficiency upgrades. The surveys involved collection of self-reported thermal comfort votes on a seven point thermal sensation scale and recording of indoor temperatures in living rooms and bedrooms twice during the day. The findings state that the efficiency measures led to increased indoor temperatures, increased thermal comfort and showed a take-back effect. The 'Predicted Mean Vote' (PMV) was found to under-predict actual thermal comfort conditions. The PMV is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale, based on the heat balance of the human body (BSI, 2005).

It has been suggested that, after receiving energy efficiency upgrades, people may consider a whole house temperature of 20°C to be the most likely comfort temperature (Milne & Boardman, 2000). Utley and Shorrock (2008) suggest that the overall comfort level in insulated, centrally-heated homes might be around 19-20°C. They also report German work which suggests that, in low energy 'passive' houses, people regard a mean internal temperature of 22ºC as comfortable. Qualitative data gathered on reported thermal comfort from the CALEBRE study (section 3.5) suggests that there may be some degree of dissatisfaction with living room temperatures in solid-wall dwellings, many of these being significantly lower than the WHO-recommended value of 21ºC.

These studies imply that, in order to improve thermal satisfaction, living room temperatures may need to be maintained within the range 20-22ºC. However, this is based on a very limited number of studies, and it is recommended that a thorough investigation of domestic thermal comfort and comfort temperatures be conducted before definite recommendations are made that inform policy.

Any increases in indoor domestic temperatures that are considered essential (on health or comfort grounds for example) should, as far as possible, be achieved by improving the energy efficiency of the house. This highlights the need for refurbishment (better insulation, reduction in heat losses and efficient heating systems and controls) as energy efficient means to achieve higher temperatures and thermal satisfaction in homes where this is needed (i.e. beneficial 'takeback' – see below). The UK Government's Green Deal Policy (HMSO, 2011) offers an important opportunity towards addressing this need.

4.4 Considerations for Future Policy

We end our discussion by offering some thoughts and comments for potential consideration in development of future policy.

The software 'RdSAP' is currently used in the UK Government's 'Green Deal' policy for assessing the reduction in energy consumption to be expected following a domestic efficiency upgrade. RdSAP calculations are based on assumed indoor temperatures of 21oC for living rooms and 18oC for bedrooms. Our finding that many actual living room temperatures during largely-occupied periods in winter and spring have been lower than the 21oC value assumed in RdSAP could impact upon expected energy savings, payback times, and consequent fulfilment of the Green Deal's 'Golden Rule'. It is recommended that consideration be given to accounting for this in domestic energy and payback assessments.

Many temperatures in living rooms during winter and spring, and for periods when occupation was likely, have been lower than that recommended by the World Health Organisation (WHO). Whilst beyond the scope of this paper, it may be reasonable to infer some connection between this and potential cost burdens upon Britain's National Health Service (NHS). Cost-benefit analyses of the return on investment that could accrue from preventing Fuel Poverty suggest that, for every £1 spent on reducing Fuel Poverty, a return in NHS savings of 42 pence can be expected from health gains (Liddell, 2008). A household is in Fuel Poverty if, in order to maintain an acceptable level of temperature throughout the home, the occupants would have to spend more than 10% of their income on all household fuel use (DEFRA, 2008). Therefore, some instances of occupant 'takeback' in the form of raised living room temperatures following an efficiency upgrade could be viewed as

beneficial, with the possibility of reduced longer-term costs to the NHS. This could open future debate as to whether people have 'a right' to be able to achieve a particular indoor temperature on health and thermal comfort grounds, with excesses being discouraged in some way.

Our evidence of there having been little change in winter and spring-time indoor average living room temperatures over the last forty years tempts one to speculate whether there might be little or no change in such indoor winter and spring-time temperatures over the coming forty years (notwithstanding any takeback effects). Viewing this scenario against the background of predicted increasing outdoor temperatures to be expected as a result of climate change, alongside increasing numbers of homes being refurbished for energy efficiency, should mean improved energy savings that will help the UK towards achieving its 2050 carbon reduction target. As regards the summer period, however, the question of overheating in refurbished dwellings is also receiving attention (Beizaee *et al*. 2013). Policymakers might give some thought as to how potential future overheating risks might be estimated and minimised as part of current policy-driven energy refurbishment interventions, together with householders being discouraged from future active reduction of summertime indoor temperatures through domestic air-conditioning, for example.

5 Conclusions

A review of measured data drawn from studies conducted over four decades on winter and spring-time living room and bedroom temperatures in UK homes has been presented in this paper together with analysis of measured data from the recent CALEBRE study. A discussion of thermal comfort in UK homes has also been presented, based on the limited data available to date. Conclusions are as follows:

- For periods when occupation was likely, little or no increase in average winter and spring-time actual living room temperatures appears to have taken place in UK homes over the last 40 years, based on reported measured data, with many recorded living room temperatures having been historically lower than the WHO-recommended value of 21ºC.

- Correspondingly, for periods of likely occupation, there appears to have been an increase in average winter and spring-time bedroom temperatures over the same period, though this is based on limited available data. This increase can likely be attributed to growth in central heating ownership, together with reductions in whole-house heat loss. From 1990 onwards, average recorded bedroom temperatures have been near to, or above, the WHO-recommended value of 18ºC. Consequently, whole-house temperatures appear to have slightly increased.

- Compared with non-domestic buildings, there have been fewer investigations of domestic thermal comfort, either in the UK or elsewhere. Based on suggestions from the limited range of studies available for the UK situation, living room temperatures may need to be maintained within the range 20-22ºC for thermal satisfaction. However, further detailed investigations of domestic indoor temperatures during occupied hours and domestic thermal comfort are required before definite recommendations can be made.

- Improving the energy efficiency of homes should be the primary means to effect such increases in winter and spring-time indoor temperatures that are deemed as essential, for example on health grounds. The UK Government's Green Deal Policy offers an opportunity to achieve this, possibly alongside enhanced thermal satisfaction. At the same time, consideration should be given to curbing excessive 'takeback'.

- Many winter and spring-time actual living room temperatures have historically been less than the value of 21oC assumed in software used by Green Deal assessors in recommending whole-house domestic energy efficiency refurbishment packages. Policymakers should consider how this might be taken into account when estimating savings and payback times within the confines of the Green Deal's 'Golden Rule'. Further considerations for future policy development should include the relationships between actual domestic indoor living temperatures, take-back, health, and future overheating risk.

Acknowledgments

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Endnotes

[1] CALEBRE (Consumer Appealing Low Energy technologies for Building REtrofitting is a four-year (2008-2012) £2 million research project funded by EON and RCUK Energy Programme (www.calebre.org.uk)

[2] Hourly average temperature was calculated by taking an average of hourly temperatures recorded across the entire sample. Maximum hourly temperature indicates the highest temperature recorded at every hour across the entire sample. Similarly, minimum hourly temperature indicates the lowest temperature recorded at every hour across the entire sample.

[3] In Figure 8, the term 'occupied' is used when measurements were taken in the presence of the householder; the term 'occupancy may vary' is used when data were continuously recorded over several or more days, with householders assumed to be coming and going; the term 'occupancy very likely' is used when the data presented is for times of day when householders are most likely to have been present (18:00 – 24:00 hrs for living rooms, 00:00-06:00 hrs for bedrooms).