

OCCUPANTS' INTERACTION WITH
LOW-CARBON RETROFITTED HOMES
AND ITS IMPACT ON ENERGY USE



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To my husband, Manos and my daughter Aiki,
and my mum, Theodosia, for their love and support

Declaration

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Abstract

Current regulatory and other policy trends in housing refurbishment relating to low-carbon performance standards tend to involve complex technologies and systems as well as innovative solutions to achieve 80% emissions reduction in line with the UK national target for 2050. Indicators of domestic energy performance tend to assume ideal performance of materials, complex systems and services, and that they are installed to high standards and under specific conditions, as well as rational occupant behaviour and interactions. Previous studies exploring the influence of socio-technical factors on the UK's domestic energy use highlight that one of the main reasons for under-performance of individual projects is the lack of understanding of how people interact with domestic technology. Considering this, and given that there is still little evidence on deep refurbishments that implement low-carbon 'whole house' approaches in the UK, this research explored occupants' interaction with heating and ventilation measures as these were designed, installed and operated. The main concern was to identify the type of interactions that occur between occupants (social housing tenants) and building systems (mainly low-carbon heating and ventilation systems), and how that influences actual energy use. Using a sample of 26 social housing properties involved in the Retrofit for the Future competition in the UK, the study employed an socio-technical mixed methods approach, in which qualitative and quantitative empirical data were explored together, cross-checking occupants' 'doings' and 'sayings'. A combination of theories was used to analyse the complex interrelated factors involved in users' interaction with building systems. The analysis identifies key factors that affect significantly occupants' everyday practices and their interactions with the new measures: thermal comfort and past-experiences with measures and controls; knowledge and skills (of both occupants and those involved in the project); design of the technical interventions (systems/measures) and

quality of their installation. The findings from this research showed that active measures (such as intelligent and conventional heating controls, MVHR boosters, etc.) fostered direct interaction with active users when there were no design or installation faults. On the contrary, low-carbon measures that are designed and installed to be passive (such as MVHR systems operation) tend, in practice, to involve indirect interactions with active users. The research findings provide an insight into the 'in-use' factors, demonstrating to policy makers and implementers of mass refurbishment programmes the need for a framework where critical combinations of different measures and design solutions are targeted on specific house types, locations and households, in order to achieve maximum savings. Higher standards in installation of the new measures and improved quality control are also found to be a key part of refurbishment policies.

Publications arising from this thesis

The following papers based upon the research reported in the present thesis have been published prior to its submission:

Topouzi, M. (2015) Deep low-carbon refurbishment challenge: what hasn't worked as designed? Proceedings of ECEEE European Council for an Energy-Efficient Economy Summer Study. 1–6 June 2015, Presqu'île de Giens, France.

A peer review conference paper presenting what has (or has not) been implemented as intended/designed, discussing the failures and successes that emerged in the 26 cases of Retrofit for the Future sample under the lenses of effectiveness in delivery, performance, occupant satisfaction and control interaction with the low-carbon building system.

Janda, K.B. and Topouzi, M. (2015) Telling tales: using stories to remake energy policy. Building Research and Information, 43(4): 516-533.

Contribution to a journal paper presenting part of the findings of one of the three real world examples presented in the paper focusing on the way narratives of actual and estimated performance are communicated and disseminated from and to policy-makers.

Topouzi, M. (2013), Low-carbon refurbishments: How passive or active are technologies, users and their interaction. Proceedings of ECEEE European Council for an Energy-Efficient Economy Summer Study, 2013, Presqu'île de Giens, France.

A peer review conference paper presenting the findings of nine cases (out of 26) focusing on passive/active users and their interaction with low-carbon technologies.

Janda, K.B. and Topouzi, M. (2013), Closing the loop: using hero stories and learning stories to remake energy policy. Proceedings of ECEEE European Council for an Energy-Efficient Economy Summer Study, 2013, Presqu'île de Giens, France.

Contribution to a peer review conference paper presenting part of the findings of one case study focusing on the way results of actual and estimated performance are communicated and disseminated.

Topouzi, M. (2011), Understanding occupants' interaction with the technical change in low-carbon retrofits: a methodological and conceptual framework. Proceedings of the ECEEE European Council for Energy Efficient Economy, Summer Study, 2011, Hyeres, France.

A peer review conference paper presenting the methodological and conceptual framework that the study has developed to identify occupants' interaction with low-carbon measures and systems.

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Acronyms and key definitions

Acronyms

DHW:	Domestic Hot Water
EST:	Energy Saving Trust
LA:	Local Authorities
MVHR:	Mechanical Ventilation with Heat Recovery
MEV:	Mechanical Extract Ventilation
RfF:	Retrofit for the Future competition programme
TSB:	Innovate UK Technology Strategy Board

Key definitions

Active design: is design that makes use of active building services systems such as mechanical ventilation, low or zero carbon systems (solar thermal systems, ground source heat pumps etc.), intelligent controls, electric lighting etc. to create comfortable conditions.

Active/passive user: users/occupants are active when their control-oriented action(s) and behavioural practices interact with heating and ventilation systems; whereas users are passive when no interaction is involved, because their practices are prefigured by either the technology or the way measures are installed.

Apparent Temperature (AT): is defined as the temperature, at the reference humidity level, producing the same amount of discomfort as that experienced under the current ambient temperature and humidity. Basically the AT is an adjustment to the ambient temperature (T) based on the level of humidity. An absolute humidity with a dew point of 14°C is chosen as a reference. If the humidity is higher than the reference then the AT will

be higher than the T; and, if the humidity is lower than the reference, then AT will be lower than T.

Airtightness of the building (or envelope): is the resistance of the building envelope to inward or outward air leakage through unintentional leakage points or areas in the building envelope. Excessive air leakage (unintentional infiltration losses) can result to increased energy consumption and a draughty, cold building environment.

Base temperature of a building: is the external temperature below which the building needs to be heated. In the UK this value for a residential building has been generally taken as 15.5 degrees, but can be as low as 10 degrees for a thermally well insulated building with large internal gains.

Brown goods: the term in British English includes light electronic consumer durables such as TVs, radios, digital media players, and computers etc.

Data loggers: Electronic sensors for physical metering of the building environment (temperature, humidity and CO₂).

Direct/indirect interaction: direct interaction is when the user/occupant interacts physically with a measure or a system's control; and indirect interaction is when the user/occupant interacts with the measure's performance indirectly via other technologies.

Combi (or combination) boiler: is a system that provides heating and hot water directly from the boiler. A combi boiler is both a high-efficiency water heater and a central heating boiler, combined within one compact unit. Its benefit compared to other types of gas boilers is the cost and time effectiveness in the installation, since there is no tank and less pipe work is required.

Condensing boiler: there are three main types of condensing boilers: combi boilers, heat-only and system boilers. Condensing boilers are far more energy-efficient than older

boilers, as they cleverly reuse heat that would otherwise be wasted. The difference between a non-condensing boiler and a condensing model is the amount of useable heat it produces from the fuel it burns i.e. a condensing boiler uses some of the latent heat of vaporisation by condensing the flue gas. The new condensing boilers are much more efficient for domestic space heating as they have a much larger heat exchanger, which extracts over 89% (to the Boiler Efficiency Rating required standard Sedbuk) of the heat from the fuel it burns, making it much more cost effective to run.

Holistic (holism): is an epistemological concept in which any entity or system is viewed as a whole greater than the sum of its component parts; the system as a whole determines how its parts behave and its operation cannot be subdivided into those parts.

Heating Degree days (HDD): is a measure of the demand for energy needed to heat a building. The integrated difference between the external temperature and the building base temperature where the external temperature is below the building base temperature gives the 'heating degree days' for a building.

Interaction: is the control-oriented action(s) between occupants' behaviours and elements of the building system.

Low-carbon buildings' design: is design that generally includes both active and passive measures to achieve low (or zero) carbon emissions during a building's lifetime.

Mechanical ventilation (or active ventilation): is ventilation with mechanical ventilation systems (MEV) that circulate fresh air using ducts extracting humid air from wet rooms i.e. kitchen and bathroom.

Mechanical ventilation with heat recovery: is an active ventilation system (MVHR) that circulates fresh air using ducts extracting humid air diverting the air from the wet rooms to heat bedrooms and other rooms in the living area.

Natural ventilation (or passive ventilation): ventilation that naturally is occurring i.e. indoor air exchange through openings (windows and doors) in the building envelope using stack and wind pressure effects.

Passive design: is design that maximises the use of ‘natural’ sources of heating, cooling and ventilation to create comfortable conditions inside buildings. It uses environmental conditions such as solar radiation, cool night air and air pressure differences for indoor comfort and does not involve mechanical or other electrical active systems. The ‘passive measures’ and key elements of passive design are: building location and orientation on the site; building layout; window design; insulation (including window insulation); thermal mass; shading; and natural ventilation. Mechanical or electrical systems are not involved in passive design or measures definition.

Performance line of a building: represents how much energy the building can be expected to use for a given number of degree days. The rate of a building’s heat losses is given by the steepness of the line (i.e. the slope) that measures of how much extra fuel will need to be consumed for an increase in degree days. The steeper the line the less likely the building is to be energy efficient and the flatter the line the more likely the building is to be energy efficient.

Retrofit for the Future competition applicants: the applicants are the RfF competition programme participants (e.g. architects, small building companies and organisations as well as housing associations) that were awarded up to £150k from the TSB and have undertaken deep refurbishment and low-carbon innovative interventions to low rise social housing to achieve RfF completion standards. The applicants were those who provided the TSB and EST evaluation process with the monitoring data, cases documentation and technical building tests; as well as they were the main contacts with the householders.

Thermal bridge (or cold bridge): are areas of the building envelope where heat transfer (heat loss) occurs through the building fabric (junctions between walls and floors, and walls and roofs) to a greater extent than through the elements being joined; and it often occurs when there is a break in the continuity, or a penetration of, the insulation.

Temperature Difference: is the difference between the internal temperature in living areas (high occupancy rooms) and the outside temperature (at the time the study's building survey was conducted).

Thermography: is a method to detect energy waste, moisture and electrical issues in buildings using an infrared camera that detects areas with energy loss, excess moisture, flood damage or electrical problems. The colours in the picture illustrate infrared radiation in which the red/yellow are parts of greater heat loss where for instance insulation is missing or poor performance of the building elements; whereas the green/blue areas indicate building parts losing less heat.

U-value: measures the heat loss performance of a building component like wall, roof, window, floor etc. The U-value measures the heat flow through a building element Watt (W) per square meter (m^2) per degree temperature difference across the element and the higher the value the more heat flows through the material whereas the lower this value is, the better the insulation provided by the building element.

White-goods: the term includes large household appliances such refrigerators or other food preservation, washing laundry and cookers.

Whole-house approach: The 'whole-house' energy efficiency approach in refurbishment means an integrated design approach and an integrated team process which helps homeowners, architects, and builders to develop and adapt successful strategies for

optimizing home energy efficiency reducing their energy needs and CO₂ impacts as a whole.

Chapter 1: Introduction

1.1 Background

From the political declarations, scientific persuasions and macro scale policies to the micro scale measures and citizens' everyday life, it is widely accepted that the climate change challenge will continue for the next decades to move forward a low-carbon society. In 2013 the residential sector was responsible for around 14% of UK greenhouse gas emissions (GHG) with carbon dioxide (CO₂) being the most prominent gas for this sector (DECC, 2015:210, Table1). The main source of greenhouse emissions in this sector from the use of natural gas for heating and cooking varies considerably with external temperature variations from year to year between 1990 and 2013 (DECC, 2015). Residential sector energy use accounts around the 30% of total energy consumption in the UK and increased by 23% over the last 35 years (Palmer and Cooper, 2011). This rate corresponds to the 26 million domestic buildings, of which 21 million will be in existence by 2050, requiring extensive refurbishment interventions to improve their energy efficiency. While the challenge of delivering low-carbon housing and substantial carbon reductions from the domestic sector has been set high, the UK having the oldest housing stock in the developed world (DCLG, 2010) needs a rate of 500,000 refurbishments every year (Killip, 2008) to achieve the 80% emissions reduction below 1990 levels by 2050 (HM Government, 2008). These considerations set out the need for households to play a pivotal role in meeting this ambitious goal (HM Government, 2008) making it extremely challenging to meet the Government's energy national targets by 2020/2050, while people are able to preserve levels of comfort and lifestyle, whilst consuming less energy.

It is clear that the existing housing stock is becoming one of the key targets in public policies. In pursuit of the UK's demanding 2020 goals, current policy trends in housing refurbishments move towards energy savings measures, regulatory or other performance

low-carbon standards and emissions reduction approaches encouraging energy savings and low-carbon incentives associated with insulation measures, smart meters, ‘Feed-in Tariffs’, heating schemes, that involve complex technologies, systems and innovative solutions. Nevertheless, performance indicators for domestic refurbishments tend to rely heavily upon assumptions of ideal behaviour of materials, combined systems installed to high standards under specific conditions, and ideal occupant behaviour in operating and interacting with them. Against the backdrop of these initiatives, several studies report that one of the major factors limiting the success of energy conservation policies is the ‘oversimplified policy analysis that has serious blind spots in the area of human behaviour’ (as cited in Stern, 1992 :1224) and a lack of understanding of how people interact with domestic technology (Lomas et al., 2006a). Other studies show that too little attention has been paid to socio-demographic and cultural factors, which can be a greater influence on how much energy is used in a household rather than the dwelling type or household structure (Randolph and Troy, 2007). However, although household occupant behaviour is a complex factor and one of the key issues in building design optimization, energy simulation and in-use performance evaluation approaches of user behaviour can no longer be considered as the only complex factor in explaining performance deficits (Gill et al., 2010).

The delivery of the national energy reduction plans is undermined by the performance gap between intended design and actual performance, as energy consumption in housing is determined by several technical and non-technical¹ (social, behavioural) interacting factors. Since the 1970s several studies from different disciplines and interdisciplinary approaches, have offered explanations based on social (e.g. socio-demographic) and technical aspects of energy use. Despite this, in the current context of domestic energy

¹ In this thesis the term ‘non-technical’ is used to describe the human dimensions involved in domestic energy use that include demographic, behavioural, social-psychological and socio-economic aspects.

studies, there is still a strong disciplinary bias towards technical and non-technical (social, behavioural) approaches.

Behavioural, socio-demographic, cultural and economic factors and their impacts on buildings energy efficiency, cover a vast area of variables. In behavioural models, energy use is conceptualised through theoretical frameworks that interpret differences as being due to consumption regimes, cultural behaviour patterns, social-economic structural conditions and lifestyles (e.g. Schipper et al., 1989, Lutzenhiser, 1992, Shove, 1998, Lutzenhiser and Gosard, 2000, DEFRA, 2008, Shipworth et al., 2009). For instance, perspectives on the performance gap might be related to the direct 'rebound effect' (e.g. Sorrell, 2007, Dimitropoulos, 2007) or the underperformance of elements in retrofitted shells (Lomas, 2010).

Similarly most of the disciplines that investigate energy use in buildings use individual building models underpinned by physical parameters of building form, fabric and systems. As Steemers and Yun (2009) argue, such approaches use rather simplistic and generalized input assumptions regarding occupant behaviour, merely occupancy patterns and internal gains. In a large number of studies the practices used in forecasting energy consumption are based on statistical averages. These averages might be useful in aggregate estimation of trends and impacts however, do not provide the detail needed to understand the underlying patterns of energy use (Lutzenhiser and Bender, 2008). Over the last forty years thermal processes in building energy performance simulation have been better understood (Degelman, 1999). However, even though these simulation models are capable of accurate predictions, especially for buildings with predictable and routine use, user behaviour still did not get much attention. Technical approaches of this kind are quite limited in some aspects, offering poor understanding of how people use energy in their households, interact with the building and adapt their lifestyle to new technologies. Most studies of energy

demand are focussed on examining technical and behavioural factors of domestic hot water, space heating and electrical appliances (e.g. Yao and Steemers, 2005, Cheng and Steemers, 2011, Shipworth et al.). Relationships between electricity used in households (e.g. in cooking, lighting and appliances) and the behaviour of end users has also been discussed widely (e.g. Cramer et al., 1984, Shove, 2003b, Firth et al., 2008, Wall and Crosbie, 2009).

Considerable work remains to identify the precise nature of these differences (technical and non-technical/social) and the ‘drivers’ involved. Some are clearly behavioural, while others implicate buildings and machines with somewhat autonomous effects (Lutzenhiser and Bender, 2008), and technical deficiencies. Very little empirical work has been done in any of these areas related to housing refurbishment over the past two decades. Both approaches, technical and non-technical (social), due to methodological constraints and lack of data, do not investigate household energy consumption as an integrated ‘household system’ (Hitchcock, 1995) or under the lens of a ‘house as a system’ approach (Janda and Killip, 2013). As a consequence, occupant behaviour is not integrated into variables related to interaction with the retrofitted measures and low-carbon technologies. As widely discussed elsewhere (e.g. Wingfield et al., 2008, Gupta and Dantsiou, 2013, ZeroCarbonHub, 2014) more integrated socio-technical holistic approaches need to be used to decrease the performance gap; and more evidence based exploration of interrelated factors is needed.

1.2 Rationale and main issues addressed

Energy use in buildings is closely linked to their operational and space utilization characteristics and the behaviour of their occupants. The occupants have influence due to their presence and activities in the building and due to their control actions, with an impact of these actions on the indoor environmental conditions (thermal, air quality, light, etc.)

(Hoes et al., 2009). The main drivers of energy use are occupants' needs and behaviour as determined by a building's physical characteristics (Hitchcock, 1993, Hitchcock, 1995). The amount of energy a household system consumes is directly dependent on the level of the different types of services (e.g. space heating, hot water and lighting) required by the occupant, along with the level of efficiency with which these services can be provided.

In the current context of domestic energy studies three key deficiencies are identified from the literature review, justifying this thesis's approach to the energy use problem:

- There is a disciplinary failings both technical and non-technical (social, behavioural) modelling approaches; technical approaches relying on the 'average' or 'default' user (occupant) to estimate energy use, fail to adequately take into account different user interactions. Similarly, behavioural models rely on conceptual approaches and theoretical frameworks that view energy use solely through behavioural and economic factors. Both models, due to methodological constraints and lack of data, do not investigate household energy consumption holistically;
- It is broadly accepted (e.g. DECC, 2011b) that the gap between predicted energy consumption (pre-refurbishment) and actual energy consumption (post-refurbishment/construction, in-use) in domestic stet (refurbishment) requires more evidence;
- The limited number of empirical studies in housing (both refurbished and new) is unable to provide better data on technical and non-technical variables with high resolution and equal weight. Thus, the level of refurbishment intervention varies significantly and deep refurbishment with low-carbon housing technologies has been undertaken only in a small sample.

Considering the above, the problem this thesis attempts to explore is the current gap between actual and predicted energy consumption in deep refurbished houses (Figure 1).

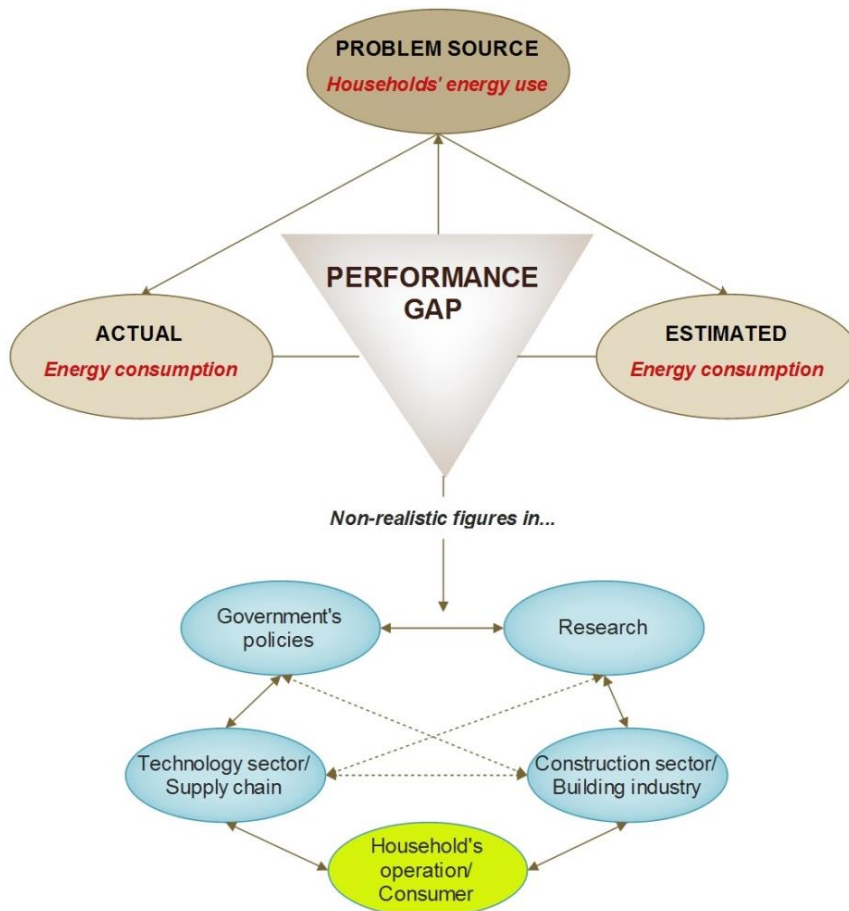


Figure 1: The current problem in studies of households' energy use and their links with different sectors.

The source of the problem stems in one sense from obvious limitations on the number of long-term² empirical studies, which are unable to provide high resolution socio-technical inputs. The effect of such limitations affects the links between different sectors related to domestic energy consumption. For instance, the design of carbon reduction policies cannot be informed by evidence-based data on their actual implementation. At the same time, the lack of in-depth post-refurbishment evaluations limits the data on how deep refurbishment interventions were carried out, as well as how low-carbon measures and technologies were installed and used. Due to this lack, it is difficult to institute an improvement cycle in

²As long-term is considered the collection of data of at least one year that can provide data on heating and cooling variations.

design, installation, maintenance and usage for both building construction and household energy technology. To a great extent housing refurbishment is still a linear process and ‘closing the loop’ (Whyte and Gann, 2001) between actual and predicted performance needs further work (Figure 2). The poor evidence-based inputs on actual performance also result in research models having to use average/default inputs and therefore being unable to inform more granular assessments.

Refurbishment process

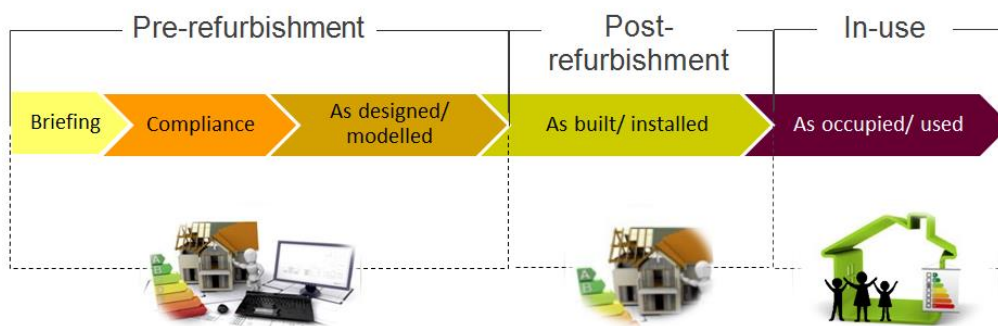


Figure 2: Main components of a linear process of housing refurbishment.

Reducing the gap will depend heavily on how accurately empirical studies can provide better data on actual behavioural patterns, buildings’ and systems’ performance and the interactions between them. Empirical studies with long-term observational data can provide behavioural trends, patterns and relationships for groups of occupants, building systems and services. This allows us to generate general patterns of user behaviour related to buildings’ energy systems. Expressed either as a set of typological aggregations or as stochastic features of actions, these patterns can provide the underlying basis for estimating user behaviour when incorporated in building performance simulation applications. However, to achieve this long-term high-resolution empirical data on occupants’ interaction with buildings’ energy systems, measured indoor and outdoor

environmental conditions and other parameters related to building systems are required (Mahdavi and Pröglhöf, 2009).

1.3 Case study context and research questions

This study aims to mitigate the household energy use data problem by using one's year high resolution empirical data, collected from low-carbon refurbished social housing projects across the UK of the demonstrator Retrofit for the Future programme organised by the Innovate UK previously known as Technology Strategy Board (TSB) (TSB, 2009). The overall intent of the thesis is to examine the type of interactions between occupants and building systems in heating and ventilation. In this, the challenge in the selected sample has been both in the type of occupants living in the properties and in the low-carbon interventions undertaken in the buildings. Social tenants have different characteristics as a social group compared to other types of occupants and tenures. Certain demographic and background characteristics (e.g. age education and income level, family composition, etc.), allocation conditions and aspects of design participation and purchasing, together with other occupancy aspects are some of the factors that contribute to different types of usage. Along with these, the technical factors (e.g. building fabric and systems) of low-carbon deep refurbishment interventions have different implications and challenges compared to typical (shallow) retrofits and new build homes. The process of deep whole-house refurbishment of an existing building system with low-carbon design solutions, and with installation of innovative technologies and control systems, is currently at a preliminary stage compared to other individual energy efficient improvements.

There is very little evidence at the in-use stage showing that low-carbon refurbishment interventions and systems' components can holistically and efficiently perform together 'as designed'/'as modelled' and 'as built' or 'as installed'. Nonetheless, it is not only the new synergies between a building's systems that need to be examined at this stage, but

also the new types of interactions between occupants, building systems and unfamiliar technologies. These interactions comprise the main area of investigation for this study that aims to identify different occupants' interactions with low-carbon systems. This is expressed with two main research questions and has two main objectives shown in Table 1.

Research Question	Research Objectives
(RQ1): What are the interactions between low-carbon retrofit interventions and occupants' behaviour?	(RO1): Identify the <i>type</i> (direct or indirect, full or null interaction/control) and <i>frequency</i> of occupants' interaction with technical refurbishment interventions;
(RQ2): Why and how does the interaction occur?	(RO2): Examine the <i>cause</i> and <i>effect</i> of these interactions and analyse the <i>interrelations</i> between socio-technical factors that determine interaction;

Table 1: The study's two main research questions and objectives.

In order to address these problems, the study developed an socio-technical methodological approach in which these questions and objectives explore user 'interactions'³ as the central phenomenon in household energy use. It investigates the type and the frequency of socio-technical interactions by examining the effect that one component has on another within a household's system.

³ As explained in the literature review chapters, in building energy use studies scholars from different disciplines (e.g. Cole et al. 2008; Lutzenhiser and Bender 2008; Mahdavi and Pröglhöf, 2009; Meir et al. 2009; Palmer et al. 2006; Stern 2000) often use the notion of 'interaction' to describe interrelated processes between technical (building fabric and systems) and non-technical (occupant/user's social, behavioural) factors related to building energy use. In many cases, however, the term is used to refer to different sets of social and behavioural factors (e.g. attitude, habit, lifestyle, knowledge, etc.), practices and building systems. In my study the term 'interaction' (energy use and operation) includes all the aspects of 'practice' (Praktik) (Reckwitz 2002: 249) in which the occupant, with his/her presence, routinised behaviours and control-oriented actions related to a building's environmental systems, affects the building's energy use flows.

In the following question the ‘why’ and ‘how’ complement each other to understand the central phenomenon of each single interaction in depth. The ‘why’ implies quantitatively identifying the cause (Creswell and Plan Clark, 2007) involved in an occupant’s interaction with a technical part and the effect of this, which explains why this interaction occurred; meanwhile, the ‘how’ examines qualitatively the interrelations between behavioural and technical variables or determinants within the interaction (see the example in Figure 3). The level of importance of each variable affecting interaction is also explored.

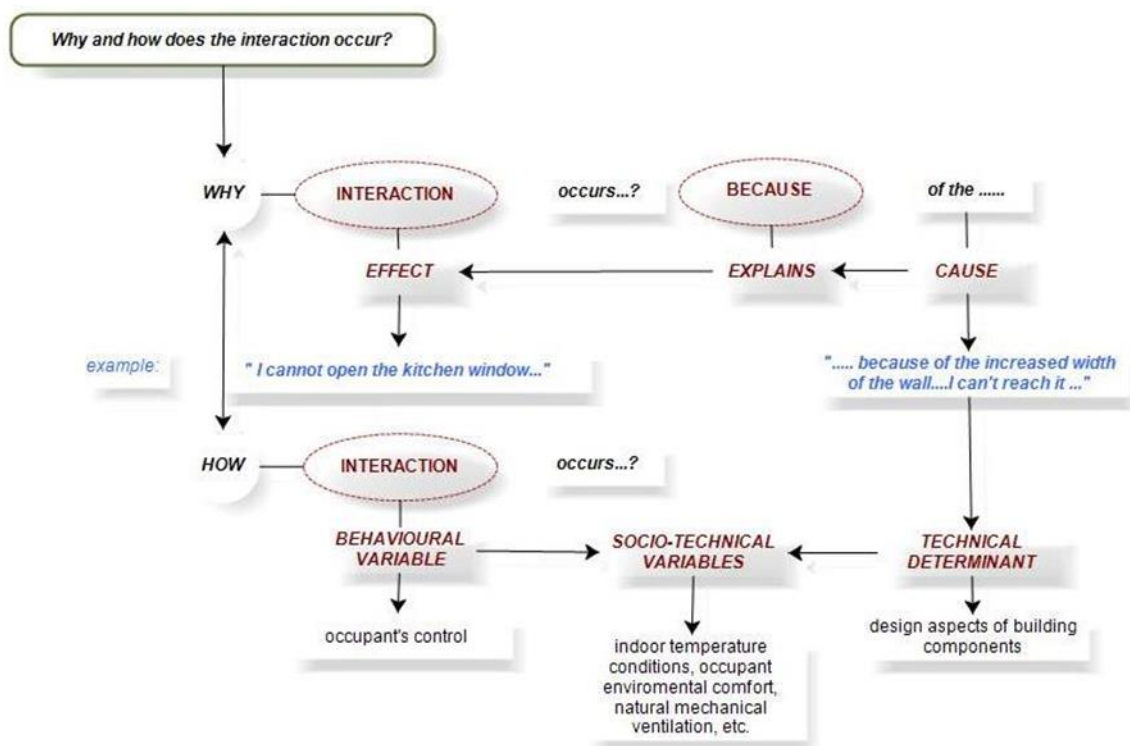


Figure 3: Example of what the question intends to capture from the data.

The overall purposes and objectives of the study (Figure 1, p.38) and the way these are linked to the current problems of research on household energy use are illustrated in Figure 4. The intent of this empirical study is to understand in-use energy in low-carbon refurbished social houses. Given the complex and disciplinarily subjective nature of socio-technical factors, the study developed a socio-technical mixed-method strategy. The purpose of this is to create socio-technical synergies and links between the different

methodological and theoretical approaches, allowing energy use to be examined holistically.

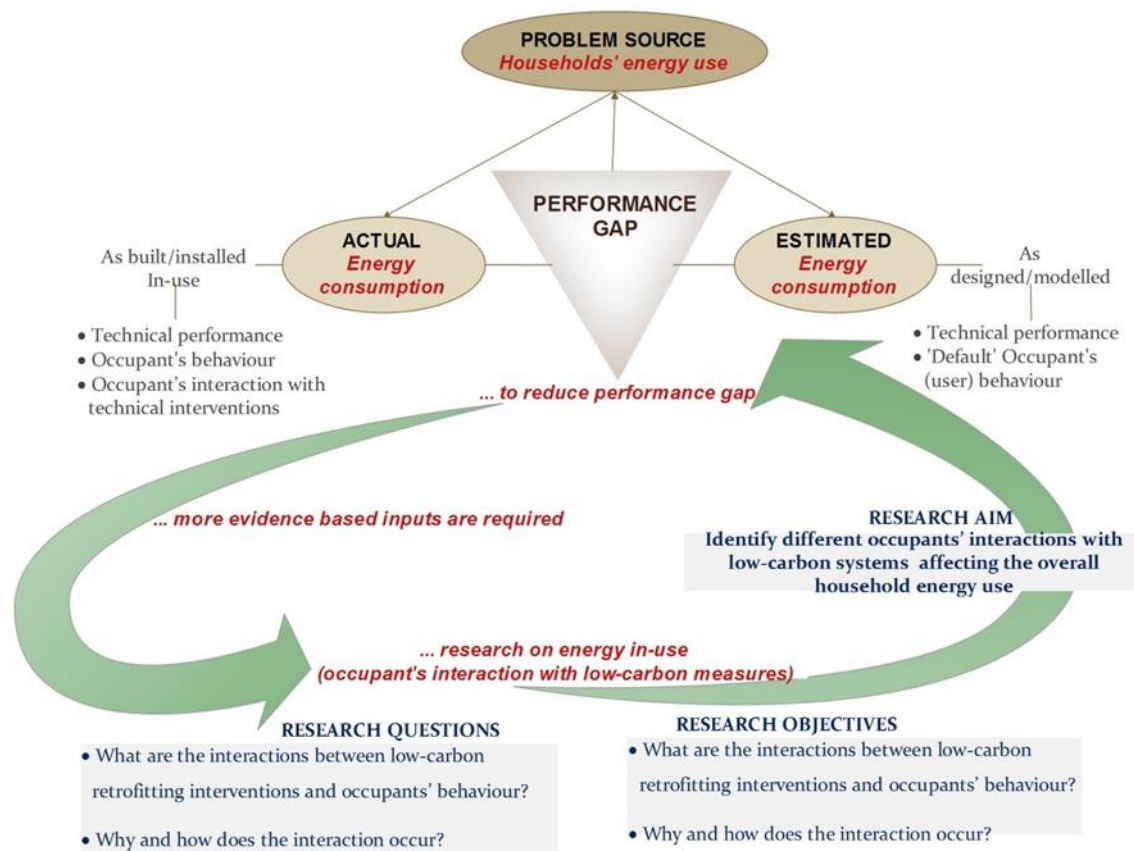


Figure 4: Problems in research on household energy use and thesis intent.

The study's conceptual framework developed as an 'intermediate theory' that attempts to connect and guide all aspects of the study's inquiry, involving the definitions of the problem and purposes, literature review, methodology, data collection and analysis. The purpose of this conceptual framework is to map the courses of action, giving the different approaches coherence in respect to the empirical inquiry. At the role of an 'intermediate theory' this framework incorporates elements borrowed from existing established social theories, previous interdisciplinary technical and socio-technical research and established methodological approaches. In this respect the theoretical approaches used in this study (such as user-centred theory, interactive adaptivity, Science, Technology and Society (STS) and practice theory) are seen as different viewpoints that complement one another

by looking at the same thing (interaction and energy use) using varying levels of detail. Methodological approaches and tools from building performance evaluation (BPE) and post-occupancy evaluation (POE) studies are used to evaluate the distance between a building's environment and a system's actual performance (in-use) compared to the predicted performance ('as designed'/ 'as modelled').

In the research design the 'interactive model'⁴ of Maxwell and Loomis (2003) was adapted to the study's mixed-method inquiry to highlight the actual relationships among the components, such as among the study's inquiry purposes, research questions, goals, and the conceptual and methodological framework. The design combines quantitative and qualitative approaches in an interactive way at all stages of investigation (i.e. research objective, goal, type of data, methods, analysis, interpretation, etc.) to understand complex aspects of energy use. Selected quantitative and qualitative approaches for data collection, from previous POE studies in households, have structured the study's toolkit of methods for the diagnostic or in-depth level of investigation.

The data collection consisted of physical and behavioural variables used quantitative approaches such as building and energy audits, along with physical monitoring and occupant surveys related to demographic information and occupancy patterns. Meanwhile, the qualitative approaches were focused on behavioural aspects related to usage (interaction) and systems controls using in-depth semi-structured interviews with the householders and observational methods in the low-carbon retrofitted properties. Triangulation methods are used throughout the data collection and analysis. The data collection involved methods using multiple techniques (e.g. semi-structured interviews along with monitoring measurements and spot checks), varied data sources (e.g. primary

⁴ In Maxwell & Loomis's (2003:263) 'interactive design' different research design components (e.g. research questions, purpose, methods etc.), tend to evolve as 'tendrils' backward and forward, integrating both quantitative and qualitative elements into all components of the research.

and secondary sources) and distinct methods of analysis and theories to allow interpretation. Similarly, quantitative (numeric) and qualitative (narrative text and images) data correlations of occupants' 'doings' and 'sayings' were explored and the links between the quantitative energy data and users' actual practices have broadened the interpretation of complex socio-technical variables. The empirical analysis in the study explored quantitative and qualitative data simultaneously in the three key areas of a building system: technical aspects (building fabric and systems), occupant (user) and interaction (energy use and operation). The empirical data collected from the RfF piloting competition programme has also offered advantages in terms of data quality, quantity and type, homogeneity, time, cost, availability and number of house cases.

Given that in this study socio-technical correlations in interaction are explored within a small number of cases (n=26), findings have not been treated as statistical generalisations. Instead they have been seen as the results of empirical evidence-based indicators of interaction between occupants (households) and low-carbon measures.

1.4 Structure of the thesis

The thesis is divided into 5 sections, consisting of 9 chapters in total. The structure of the thesis is illustrated in Figure 5 below.

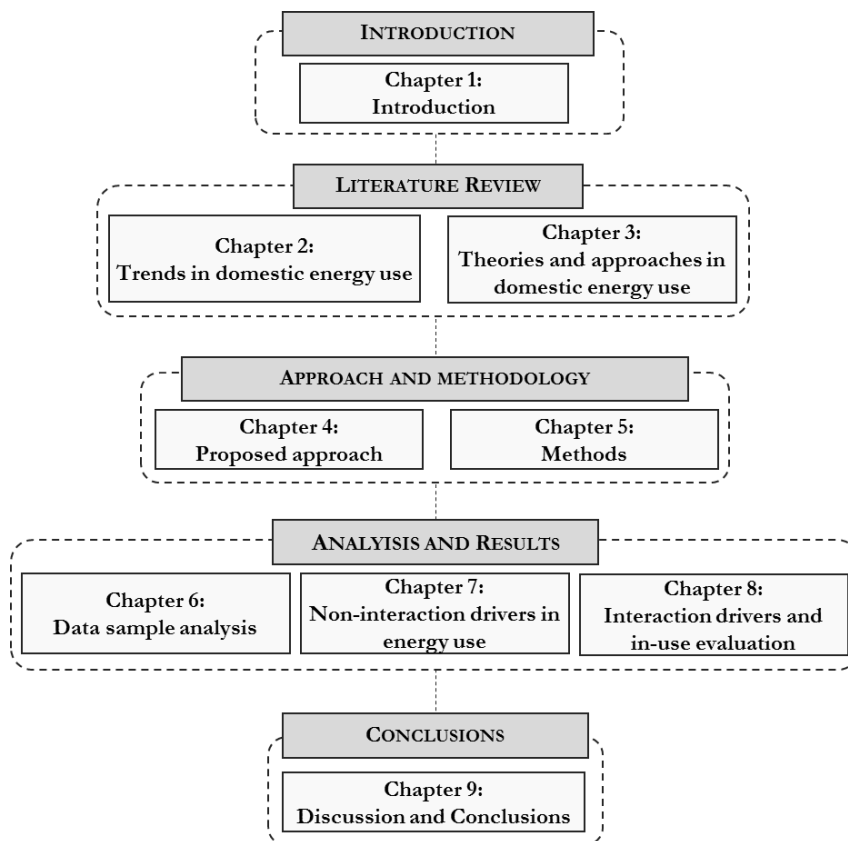


Figure 5: Structure of the thesis.

Introduction

In this section **Chapter 1** sets out the general arguments and motivations, discussing the background of domestic energy use and identifying the problematic aspects of current approaches. It contextualises the issues involved in household energy use that lead to the current gap in research and the ways these form the study's research aims and objectives. An overview of the rationale for the thesis's approach and a brief outline of the proposed research methodology, are followed by an overview of the main issues addressed by the study.

Literature review

In this section the selective literature review consists of two chapters. **Chapter 2** discusses the context for the UK's domestic energy use and the current energy policy trends in social

housing refurbishment. It provides a brief overview of current social housing, focusing on the physical conditions and energy use profile, as well as the socio-demographic characteristics of social tenants. **Chapter 3** starts with an overview of the different interdisciplinary research approaches, models and methods related to domestic energy use and the study's objectives. This is followed by an extended review of theories, methodologies and techniques used in technical, non-technical (social and behavioural) and socio-technical approaches. It provides the background that led to the study's theoretical and methodological structure. Based on previous studies technical, non-technical and socio-technical variables and dependencies related to user interaction in a household's energy use system are also introduced. The discussion of building performance evaluation (BPE) approaches provides the rationale for the evaluation methods and techniques that the study undertakes to collect the empirical data. This section concludes by outlining the main issues identified in the review, which are examined and established in the following sections.

Approach and methodology

The two chapters in this section describe and set out the preparatory and exploratory phases of the study. **Chapter 4** provides the research design and the rationale for an interdisciplinary socio-technical conceptual framework that connects and guides all aspects of study's inquiry involving the problem and purpose definitions, the literature review, methodology, data collection and analysis. It introduces the dataset of the Retrofit for the Future (RfF) competition programme, justifying the selection of the specific 26 RfF deep refurbished properties used within the sample.

Following this, in **Chapter 5**, the study's methodology is divided into two main stages, data collection and data analysis, which were undertaken in parallel in the research

process, complementing and informing each other. In data collection, the design of building performance evaluation methods and techniques undertaken is presented. The outcomes drawn from the pilot survey and the way these have contributed to the main survey design are also discussed. In the main survey design there are three main subsections: the building survey section explains the objectives of the selected methods in capturing, at the post-refurbishment in-use stage, the ‘as designed’ and ‘as built’ aspects of the building fabric; the energy audits and energy assessment survey section presents the tools and sources that provided information on the ‘as modelled’/ ‘as designed’ performance of the building; and finally the occupant survey explains how the corresponding semi-structured questions in the in-depth interviews were designed in relation to the variables and the research inquiries. A discussion of different analytical methods and techniques used to explore different types of interaction events follows later in the chapter. Thematic analysis techniques are used to discuss the data in rich detail as organised within the key areas, themes and subthemes that emerged from the sample of the twenty-six RfF deep refurbished properties. Evaluation and classification of determinants related to certain attributes in identified thematic groups (e.g. buildings’ type of low-carbon equipment, occupants’ health status, composition etc.) enable correlation, regression analysis and comparison techniques to explore relationships between variables and similarities as well as differences between these groups.

Analysis and results

This section reports on the data analysis outcomes and comprises three chapters, each of which describes the different phases of analysis to attain the empirical findings. The first part of **Chapter 6** provides a descriptive account of the sample in terms of data validity and reliability, discussing the issues that emerged from all data sources and data types. This is followed by a presentation of a case study as an exemplar of the depth and structure

of the analysis undertaken in the study's sample (n=26). The main analysis is presented across the two following chapters. **Chapter 7** discusses the non-interactive drivers in energy use of the RfF households along with characteristics related to their technical and non-technical factors pre and post-refurbishments. The factors that have no direct interaction with users but shape the building's system context in which interaction is taking place are presented in this chapter. **Chapter 8** then provides the final analysis using considerations from the previous chapter, along with the socio-technical factors in occupants' interaction with the low-carbon measures installed. It provides the actual performance of the refurbished buildings in-use arising from occupants' (or household) interactions. The evidence-based empirical findings present the main links between technical and non-technical variables, as interpreted by the study's socio-technical approach, which affect user interaction with heating and ventilation measures.

Conclusions and discussion

The thesis ends in **Chapter 9** with a review that brings together all the main findings and strands of evidence. This is done by assessing the intent of the study, the final findings and the overall contribution of the methodology and conceptual framework in all stages, which led to households' interaction patterns and evidence-based indicators of the interaction with low-carbon measures to be emerged. The success criteria and limitations of this research are discussed and suggestions for future work are also made. The thesis finishes by providing some key messages and recommendations for different sectors involved to low-carbon refurbishment.

Chapter 2: Trends in domestic energy use

This chapter provides the relevant background issues for this research. Short and long term energy policies and the UK Government key incentives related to building fabric and heating measures efficiency are first discussed along with the assessment methods, regulations and standards employed for reducing carbon emission in housing. This is followed by a discussion on the current trends in household energy use in the UK by end use; while thermal aspects of energy use and heat loss parameters related to building fabric are also presented in this section. A review of the current social housing sector highlights issues in socio-demographic characteristic related to social tenants' economic and occupational status, occupancy, age and family composition, and ethnicity proportions. The technical determinants affecting domestic energy use related to social housing building condition, age, type, area and location are also reviewed. The proportion of heating and insulation measures and their effect on energy performance are also explored.

2.1 The UK's policy background in housing

Government action measures range from those included in the Fuel Poverty Strategy 2001, the White Paper 2007 and Climate Change Act 2008, to the UK Low-Carbon Transition Plan launched in 2009 and the current Energy Act in 2011. The discussion on the UK's policy background in this section goes back in 2001 the time when in the government's housing policies elements of retrofitting and energy efficiency interventions start been included.

In 2001 the UK Fuel Poverty Strategy set out the Government's policies for ensuring that there won't be households in fuel poverty⁵ in England by 2016. A suite of policies

⁵ According the new definition of fuel poverty reviewed by Hills states that a household is said to be in fuel poverty if: a. they have required fuel costs that are above average (the national median level) and b. were they to spend that amount they would be left with a residual income below the official poverty line. The new

included in this Strategy targeted the three main factors that influence fuel poverty – household energy efficiency, fuel prices and household income (DECC, 2011d, DECC, 2014). The fuel Poverty Strategy officially defined for the first time the phenomenon of ‘fuel poverty’, not as an isolated social problem but as a problem closely linked with energy efficiency programmes and initiatives for sustainable housing. A shift in emphasis in the Government’s programmes actually began, in 2002 by the Energy Efficiency Commitment (EEC) moving from an energy saving focus to one of carbon reduction (Stockton and Campbell, 2011). The Climate Change Act 2008 imposed a legally binding obligation to reduce carbon dioxide emissions by 34% by 2020 against 1990 levels. This was followed by the UK Low-carbon Transition plan launched in 2009, built on Government’s commitment which committed to insulate six million households by the end of 2011 and the main delivery mechanism was cash back schemes from energy suppliers until 2012. This was also followed by long term policies setting out a new goal of cutting residential emissions by 29% from 2008 levels by 2020. The Coalition Government in 2010 committed to continuing to tackle fuel poverty and supporting vulnerable households to heat their homes at an affordable cost setting out a number of policies and schemes in place to help vulnerable groups. The current Energy Act 2011 introduced a ‘green flag’ of policies like the Green Deal and the Energy Company Obligation (ECO) that were widely seen as a failure (e.g. Dowson et al., 2012a, Gardiner, 2012).

The CO₂ reduction commitment in households was aimed to be delivered through a number of Government incentive schemes and programmes. Some of the schemes were focused on renewables, like the Renewable Energy Strategy (RES), Micro-generation Certification Scheme (MCS), Renewable Heat Incentive (RHI) and Feed-in-Tariffs (FITS) (HMGovernment, 2009). The Boiler Scrappage Scheme, launched in 2010, involved the

definition also uses a fuel poverty gap. This is the difference between a household’s ‘modelled’ (average) bill and what their bill would need to be for them to no longer be fuel poor.

funding of up to 125,000 households to upgrade their boiler (new boiler or the replacement of a working G-rated boiler with renewable heat unit). Others were more focussed on upgrading house fabric efficiency including the Carbon Emissions Reduction Target (CERT), Warm Front, the Decent Homes Programme, the Community energy saving programme (CESP), and the Green Deal. Some of these schemes, targeting vulnerable household groups in either social housing or the private sector, mainly promote insulation and other energy efficient measures in the building fabric. Such schemes and programmes were and continue to be the main policy instruments for improving housing energy efficiency and meeting the Government's transition plan objectives. Some of the latter Government's key incentives are discussed below.

2.1.1 Carbon emissions reduction target (CERT)

CERT was the UK's main energy efficiency mechanism and operated from 2008 to December 2012 (DECC, 2011c). The extended scheme was restructured increasing the target by 108 Million lifetime tonnes of CO₂ target and setting a new ambitious target of 293 MtCO₂ (Dowson et al., 2012a). Domestic energy suppliers had a pivotal role in this and had to reduce their customers CO₂ emission by promoting the uptake of low-carbon energy solutions to households. CERT was especially important for social housing, as it focused delivering measures on a 'Priority Group' of vulnerable and low-income households including those in receipt of eligible benefits and pensioners over the age of 70 and to a 'Super Priority Group' of households at high risk of fuel poverty (DECC, 2010b). In this regard, 25% of professionally installed CERT measures were delivered to social housing tenants (primarily Priority Group) through Registered Social Landlords (RSLs)⁶ (DECC, 2011c). By March 2011 approximately over two million lofts and 1.6 million cavity walls

⁶ The RSLs, which include local authorities in their role as landlords, have legal responsibilities to meet 'Decent Homes' or equivalent standards for social housing, and have therefore tended to support energy efficiency improvements in their properties, often as part of wider renovation programmes.

were professionally insulated⁷; whereas only 39,700 households had solid wall (internal or external) insulation measures installed. The figures for insulation measures installed for the period 2008-2012 in Figure 6 below show that CERT was mainly successful at installing cavity wall and loft insulation compared to previous energy efficiency schemes. However, there was less delivery of heating measures, with 70,000 households having fuel switching measures (to gas central heating) and about 5,000 heat pumps installed (DECC, 2011c).

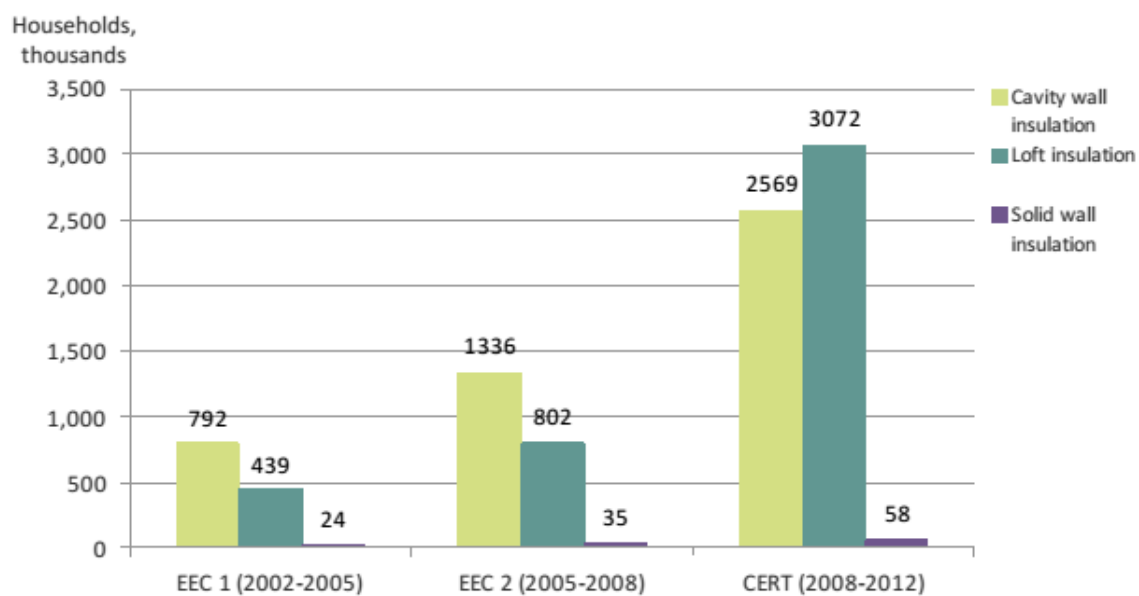


Figure 6: Insulation measures installed under the Energy Efficiency Commitments (EEC1 and 2) and Carbon emissions reduction target (CERT) in UK (source: Palmer and Cooper, 2013).

2.1.2 Community energy saving programme (CESP)

CESP announced in 2008 was a three-year retrofitting programme funded through an obligation on major energy suppliers and involving for the first time electricity generators in order to offer free or low cost energy efficiency measures in certain low income areas. The community approach in CESP required suppliers and generators to work in partnership with local authorities and other community organisations to promote energy efficiency measures targeting low income, deprived areas and often hard-to-treat-homes. A

⁷ Some of the households have received both wall and loft insulation measures installed.

‘whole house’, intensive approach was promoted, incentivising installation of using a house by house and street by street approach. A wide range of energy efficiency measures was used including wall, loft and floor insulation, draught proofing, high efficiency glazing, heat pumps, fuel switch (to gas) and boilers replacement, micro-generation measures (PV, solar thermal, micro CHP, biomass boiler, micro wind, etc.), heating controls, linking or upgrading properties to a district heating system and providing home energy advice. There was slow initial implementation of the programme with the main activity taking place from the beginning of 2012, i.e. its final year (Watson and Bolton, 2013a). Although initial target was not met, as energy companies had a shortfall of 15.3%, this was better than may have been predicted in June 2012. (DECC, 2011a). According to Ofgem (2011) figures a total of 293,922 measures were installed in 154,364 dwellings in low income areas with the most prevalent measures in 81% of scheme submissions including external solid wall insulation, 65% of heating controls and 62% boiler replacements.

2.1.3 Decent Homes

In 2000 the Department for Environment, Transport and the Regions (DETR) published its Housing Green Paper, *Quality and Choice: A Decent Home for All* (Davidson and Piddington, 2007, National Audit Office, 2010, DCLG, 2012a). The Government’s aim with this was to bring change in the quality of the housing stock, with about 95% of social housing stock in England to meet by 2010 the Decent Homes standard. Significant progress was made three years later with *Decent Homes: Definition and guidance for implementation* (2006) following up the 2004 Decent Homes Programme, which focused on policy amendments seeking to clarify issues raised by the implementation of the programme. The guidelines set out the minimum standards that needed to be delivered in refurbishments and set a Decent Homes Standard as an energy performance benchmark for

social housing. The issues addressed the age and condition of building's fabric and structure, the age of facilities and domestic services, from the adequacy of the room size to the dwelling layout. In addition, to achieve thermal comfort standards, the requirements for insulation and for efficient heating (specifications for energy efficient heating sources, systems, and materials) were set out. In 2010 several local authorities and housing associations started adopting the revised new version of 'Decent Homes Plus' standard, including additional energy efficient measures (e.g. double glazing, energy efficient doors and opening draught proofing, energy efficient boiler and full heating controls, efficient lighting, sound insulation etc.).

The number of 'non-decent' homes in the total stock in England declined from a 35% in 2006 to 30% (6.7 million) three years after (DCLG, 2011b). The latest English Housing Survey report (2012) shown 22% (4.9 million dwellings) still failing to meet the standard (Appendix 3). In this context, in the social rented sector at the start of the programme there were around 1.6 million 'non-decent' homes representing 39% of all social housing (NationalAuditOffice, 2010). In April 2011 although social housing sector has the lowest proportion (around 17%) of the total stock (DCLG, 2014b, DCLG, 2014d) extra help of a £1.6 billion was allocated by the Government to local councils to boost improvements in 217,000 council houses to achieve Decent Homes standards by 2015; and further £160 million allocated for 2015 to 2016 (DCLG, 2012a).

The implementation of the Decent Homes programme involved significant change to the social housing sector. Over these years it moved from a generic to a socio-technical indicator for social housing decency, has now moved towards more detailed low-carbon development measures. However, the concern is still about the interpretation and implementation of these strategies. Such concerns have led studies –commissioned by the Department of Communities and Local Government and the Housing Corporation– to a

detailed exploration of how these strategies are implemented, interpreted and coordinated alongside other policies, strategies and other local authorities (LAs) priorities (Davidson and Piddington, 2007).

2.1.4 Warm Front

The Warm Front scheme first launched in June 2000 (ended in 2013) was a Government funded programme that aimed to tackle fuel poverty by improving energy efficiency in vulnerable private sector households (privately owned or rented) in England. The scheme was available for properties with Standard Assessment Procedure (SAP) rating of 55 or below (at energy efficiency rating band D or below). The scheme was targeted at households in fuel poverty and vulnerable groups. Qualifying households were eligible for grants⁸ up to £3,500 including loft insulation, draught proofing, cavity wall insulation, hot water tank insulation, gas, electric, liquid petroleum gas or oil heating systems or up to £6,000 where oil central heating and other alternative technologies were recommended. By the end of March 2012 a total of 2.3 million households in England, or 11% of all households received assistance. The most common types of intervention were loft insulation (0.7 million), draft proofing (0.6 million), cavity wall insulations and replacement boilers (both 0.5 million). The scheme was criticised as nearly 75% of households who qualified were not in fuel poverty (Watson and Bolton, 2013b). Another strong criticism was the failure to provide a full range of measures (e.g. external wall insulation) for hard-to-treat households.

2.1.5 Green Deal Plan

Although the Green Deal Plan energy efficiency programme was announced by the new Government in 2010 it formally began its operation in 2013, using a market-based and

⁸ Eligible applicants did not have to pay anything when the cost of the work was not exceed the grant available; whereas for the cases in which the cost was higher from the awarded funding the household had to make a contribution to enable work to go ahead.

demand-led financial mechanism (Mallaburn and Eyre, 2014) to enable private firms to offer consumers energy efficiency improvements to their homes through a financing pay-as-you-save (PAYS) incentive for energy bills. The fundamental principal, the so-called ‘Golden Rule’, of this plan is that ‘the expected financial savings must be equal to or greater than the costs attached to the energy bill’ (DECC, 2010a). Alongside with the Green Deal, the Energy Company Obligation (ECO) replaced previous CERT and CESP programmes to provide additional financing support to vulnerable low income households and hard-to-treat properties (Dowson et al., 2012a). At the end of December 2013, the impact of this programme was less successful as there is only 1,612 households having Green Deal Plans either in progress or ‘live’ (Hough and White, 2014). However it is still in operation rendering it difficult to evaluate the implementation side for the housing sector and its content in relation with preceding schemes.

2.1.6 Energy policy aspirations in social housing refurbishment

In addition to Government’s policies and in line with the 2020/2030 vision, there has been a series of statements like the Warm Homes, Greener Homes plan in 2010, launching strategies and measures for energy efficiency improvements in households. In this plan, the social housing sector was required to reach more demanding standards to tackle carbon reduction emissions and fuel poverty. This resulted in a new ‘Warm Homes’ standard to supplement the existing Decent Homes Standard and to guide social landlords to meet higher energy efficiency by 2020. Although quite generic at its inception, covers issues on the building fabric, including standard insulation, evaluation of fabric measures that each case requires and renewable heating systems or connection where feasible to low-carbon district heating. In addition, under the vision to reduce social housing emissions and tenants’ bills, and enable the industry to roll out low-carbon technologies, it proposes a rise in the levels of the Government’s Standard Assessment Procedure for Energy Rating in

Dwelling (SAP). Other aspirations like the ‘Great British Refurb’ campaign launched the Government’s ambition for long terms plans for domestic heat and energy savings by 2030. The aim of this was a ‘whole-house’ package for all homes including a series of cost-effective energy measures (from building’s fabric insulation strategies, high performance glazing systems to smart metering systems), renewable and low-carbon heat and electricity measures as appropriate (from LZC’s technologies to energy efficiency appliances) (HMGovernment, 2009). Although the Warm Homes and Energy Conservation Act 2000 was the catalyst for the UK Fuel Poverty Strategy published in November 2001 according to the UK Fuel Poverty Monitor 2013 (NEA and EAS, 2013) findings the Government has been criticised of failing to meet its duties on both.

The need to retrofit existing homes on a massive scale as discussed elsewhere is clear; fuel-poor homes in the social housing sector in particular are suggested as the starting point for a mass-retrofit scheme across the UK (Jenkins, 2010). However, compared to other types of tenures social housing refurbishments are still driven by much weaker requirements of the Government’s schemes and funded programmes, and in line with Decent Homes standards requirements. Although the UK’s low-carbon policies have been susceptible to frequent change and updated measures and goals since 2001 to date, the social housing refurbishment framework seems to be subject to less radical changes and is more amenable on the implementation side of these measures.

2.1.7 Assessment methods, regulations and standards in housing

One of the weaknesses that often constrain implementation is the mismatch between the current assessment methods and rating systems, regulations, and standards for the energy performance of buildings, discussed in this section.

a. Assessment methods

The environmental assessment method of UK's buildings for over 20 years has been BREEAM (the Building Research Establishment Environmental Assessment Method) with Eco-Homes being BRE's method for housing (both new and refurbishments). Although Eco-Homes method was launched in 2000, it became mandatory for social housing in 2003. The Eco-Homes (major refurbishment) and Eco-Homes XB 2006 (minor interventions) are both based on a rating system that encourages a range of actions for building performance and environmental impact improvements. The assessment falls in seven categories, Energy, Transport, Pollution, Materials, Water, Land Use and Ecology, Health and Wellbeing, using SAP for the energy performance calculation. In June 2012 the Eco-Homes scheme was replaced by the BREEAM Domestic Refurbishment scheme a design and assessment method that provides the methodology, software tool (BREDEM, see Appendix 2) and certification for the delivery of sustainable domestic refurbishment.

The Government's Standard Assessment Procedure for Energy Rating in Dwellings (SAP) is the usual metric of building energy performance (see Appendix 1). Other rating schemes include the Energy Performance Certificates (EPC) introduced in 2007 under the EU directives. This rating system for a dwelling's overall performance and emission levels also requires SAP methodology for its estimations. Until 2010 the EPC was a requirement only for new lettings and sales but not for refurbishments; however, the energy performance certificate is now also required for existing building interventions.

b. Building regulations and standards

The minimum standards for refurbishment intervention in existing buildings set by building regulations vary across the UK (England, Wales, Scotland and Northern Ireland) and are subject to different technical performance requirements, definitions and procedures. The building work guidance for England and Wales is provided by the Part

L1B for existing buildings, in Scotland and Northern Ireland, through a system of technical handbooks. Building regulations became mandatory in England in 1966 mainly in response to improve public health other than buildings energy efficiency. Minimum standards and requirements for new and existing buildings were progressively raised after the energy crisis in 1973. The role of the building energy regulations is to set the minimum standards for the physical components (i.e. walls, roof, windows, heating and DHW systems and controls) in building fabric interventions (i.e. renovation, conversion, or extension) and for other building services (i.e. lighting). Successive amendments have set out the minimum *U*-value standards to limit infiltration heat losses through the walls, roof and floors; while windows beyond single glazing as well as additional measures concerning a building's air tightness and thermal bridging have been set as a requirement in the 1990 Building Regulations (Dowson et al., 2012a). Changes to the 2010 Building Regulations increased the levels of insulation (and air tightness) of new homes. Energy efficiency standards for new homes were improved by 25% in 2010, and the proposed changes to the 2013 Regulations range from an 8% to a 26% improvement relative to 2010 standards (Palmer and Cooper, 2013).

Independent non-profit companies or groups such as the Energy Saving Trust (EST) and the Association for Environment Conscious Building's (AECB) have also set out a suite of recommended refurbishment standards. These standards provide policy trends delivering higher energy standards and design guidance for buildings refurbishment. EST's requirements set 'good practice' and 'advanced practice' for buildings' physical components (e.g. insulation, windows, heating systems etc.), offering useful design guidance for achieving lower energy refurbishments. The AECB Energy Standards set a more robust whole building energy approach (Silver and Passivhaus house standards) for refurbishments (AECB, 2007). Both standards provide quite straightforward and

transparent guidance and useful advice on how to achieve high energy and CO₂ performance in refurbished buildings. In this respect, at the design stage, AECB's Passivhaus, for instance, provides a more specific energy performance standard, for very high levels of energy efficiency, compared to BREEAM and ECO-Homes (or Eco-Homes XB), in which the overarching sustainability assessment ratings address more broad environmental issues. In several UK projects, practice has proved that by implementing Passivhaus standards the building fabric achieves higher levels than those of BREEAM and ECO-Homes. A comparison between the Building regulations requirements and Passivhaus standard is provided in Table 2 below.

Building components	2010 Building Regulations Part L1A and Part L1B	German Passivhaus standard
Orientation and shading	Not considered	Passive solar design principles
Walls, roof and floor	U -values of 0.25-0.3 W/m ²	U -values of ≤ 0.15 W/m ²
Openings (windows and doors)	U -values of 1.8-2.2 W/m ²	U -values of ≤ 0.8 -0.85 W/m ² with solar coefficient of 0.5
Air tightness	Air change rate of 7-10m ³ /m ² h@50Pa	Air change rate < 1 m ³ /m ² h@50Pa
Whole house heat recovery	Not considered as buildings do not achieve air change rate below 3m ³ /m ² h@50Pa	Efficiency of $\geq 75\%$ (Calculated according to the Passivhaus Institute methodology). Incoming fresh air pre-heated to $> 5^{\circ}\text{C}$
Lighting and appliances	Low energy lighting and C+ appliances	Low energy lighting and C+ appliances
Total heating demand (space heating and hot water)	~ 55 kWh/m ² /year	New build of ≤ 15 kWh/m ² /year. Retrofit of ≤ 25 kWh/m ² /year

Table 2: England and Wales Building Regulations compared to the Passivhaus standard (based on: Dowson et al., 2012b).

Housing energy policies to date are mainly focusing on replacement of elements like loft and wall insulation and central heating systems upgrade but not on complex issues related to deep refurbishments that this study will cover using the Retrofit for the Future dataset as a case study exploring a whole-house approach in deep refurbishments. Energy policy

trends in the UK’s housing sector discussed in previous sections are summed up in Figure 7 below to illustrate how the different ‘drivers’ and ‘tools’ are linked together.

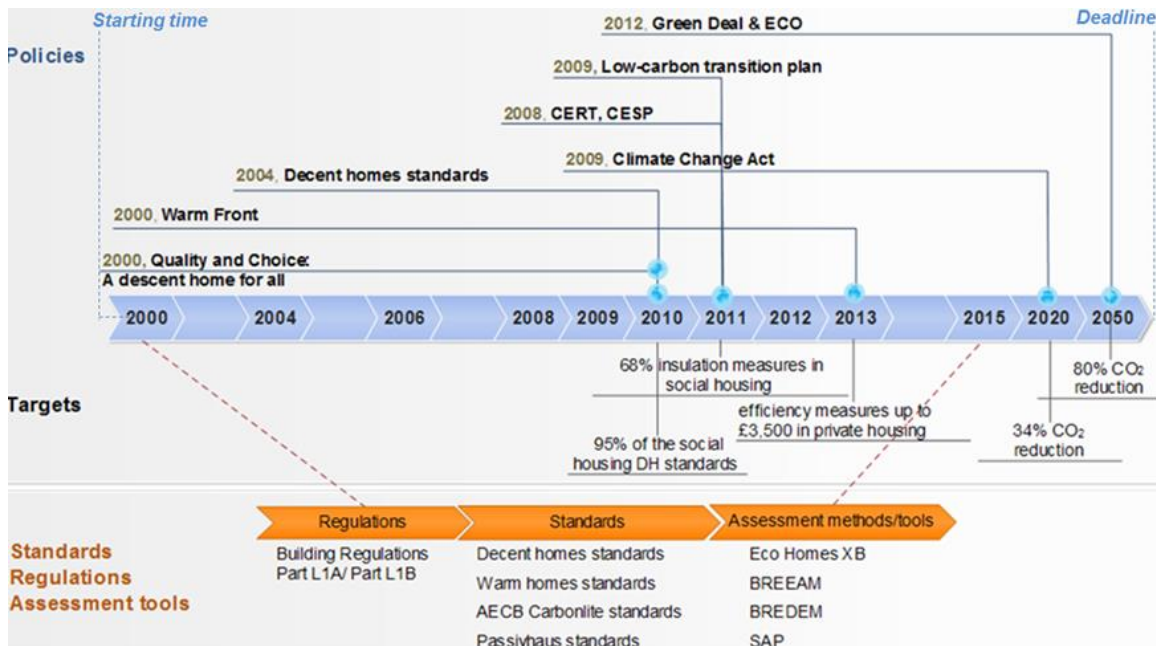


Figure 7: The UK Government’s framework of policies, targets and standards in domestic energy use.

As it can be seen buildings’ sustainable development consists of an iterative mechanism in which policy targets are dependent to a large extent on the synergies among the set of standards, regulations and assessments methods and tools.

2.1.8 Building’s design and refurbishment approaches

Relying on the ‘stability’ of physical criteria to make houses ‘more efficient’ does not mean ‘lower energy use’ (Moezzi and Diamond, 2005, as cited in, Moezzi and Lutzenhiser, 2010). Clearly the distinction between technical scenarios depends on whether the occupant’s role is more active or passive. Studies looking at occupants’ comfort come across a design process which ‘is delineated by shifting the design responsibility from architects to mechanical engineering consultants and control responsibility from occupants to technology’ (Cole et al., 2008:324). In building design there is an intended (but not always clear and successful) hierarchy of the different levels

of intervention and professions to improve building's efficiency; however, the user (occupant) often is found at the bottom line of this hierarchy and assumed to operate the building with the consequences of all these design decisions (Leaman, 2005). Design aspects become even more important in the cases of social housing, where the users (occupants) often have very limited (to null) design choice and participation in the decision of the technical interventions. In these cases the occupant has to operate, interact, and adapt his or her needs and lifestyle in the overall building's technical system which has been determined and invested in by others (housing associations). The role of social housing occupants in a whole design process and refurbishment, in terms of decision-making (in layout, measures, technologies etc.), cost investment, personal commitment and level of usage information, can deviate significantly compared to private owners.

Another aspect that ends at the bottom line of this design hierarchy together with the user is the after-build maintenance service provided to the householder. In the property/construction sector, for the private housing this is often known as 'after-sales service', which in the case of social housing is traditionally covered by housing authorities' technical support. Another aspect that needs to be considered is that for some of the new technologies, the construction and technical sectors are still at an embryonic stage (e.g. combined low-carbon systems) lacking in specialised expertise and experience. Such aspects of design and service are the subject of this empirical study and discussed in detail in following section.

a. Terminological plurality in buildings' intervention

From conceptual perspective of the design process another problem identified is the plurality of ways current language describes the design processes of efficient technical interventions in buildings; this can constrain communication and the occupant's understanding of what technical interventions these terms actually describe.

From a literature review of Governmental documents and published works mainstream terms, we find neologisms such as ‘sustainable refurbishment’ (EST, 2010a, EST, 2010b), ‘low-carbon retrofit’ (Alliance, 2010, TSB, 2009), ‘deep energy retrofit’ (RockyMountainInstitute, 2010), ‘eco-upgrade’ (DCLG, 2010, DECC, 2010c, DECC, 2010a), ‘eco-renovation’ in interchangeable combinations; these are the commonly used terms to describe the concept of work undertaken to improve the energy performance of an existing building. However, these terms neither clearly define the level of intervention and improvement nor describe the activities or measures that need to be installed to attain such improvements. Certainly with energy language evolving and with such activities being at early stage of development, ‘fluidity’ and ‘non-standardization’ in the terms used does not necessarily indicate a significant difference of meaning (Fawcett, 2011).

Therefore the ways refurbishment, retrofit and renovation are currently used overlook the classification found in engineering and architectural disciplines, which are associated with the different ‘levels of intervention’ to the building. From an engineering viewpoint the term ‘refurbishment’ is seen as the process that includes all of the intervention elements in both deep and conventional technical intervention (large or small scale). From this perspective the term ‘refurbishment’ is used to describe a building’s improvement above and beyond its initial condition. More specifically, it is the process of extending the useful life of an existing building through the adaptation of its basic forms by providing a new or updated version of the original structure. The scale of intervention varies depending on the project (e.g. condition, shape, size location of the existing structure, intended use of the structure, compliance with current building regulations, listed etc.). The term ‘building retrofit’ describes the process of changes by fitting new and more modern systems inside the building after its initial construction and occupation; the term is commonly associated with building’s services improvement, accepting that ‘the life of the building structure and

fabric will be considerably longer than that of the installed services' (Riley and Cotgrave, 2011:5-6). When the 'deep energy retrofit' term is used, this commonly describes an integrated design approach to improve the energy efficiency, which aims to achieve much larger energy savings (at least 60% operating cost savings) than 'typical' energy retrofits (achieving 20-25% energy savings) (RockyMountainInstitute, 2010). For cases that implement new technologies, the term 'sustainable retrofit' is sometimes used, implying reductions in energy and water usage for the retrofitted building. With 'renovation' the term implies merely renewal and repair works; in such interventions the work is carried out to improve dilapidations and to avoid further degradation of the building (Riley and Cotgrave, 2011).

Although the plurality of these often interchangeable terms may have less direct impact on social occupants (compared to private householders) as the whole process is undertaken by RSLs. Nonetheless, it creates barriers to knowledge and information, as such definitions can limit the understanding of what are the key components in such interventions or the level of the whole improvement process. Therefore, the type of measures associated with each of these terms needs to be explicitly defined to help efficient communication between and within technicians, engineers and professionals, industry and policy makers and occupants (users).

2.1.9 Trends in domestic energy consumption

Although in the past 40 years the number of households increased by 44%, energy use for heating (space heating and hot water) has increased just over a tenth (Figure 8) implying that building fabric and heating system efficiency improvements have largely offset the effect of household growth and the demand for warmer homes. Insulation improvements and increased efficiency of heating systems have provided better comfort levels, by increasing internal temperature by an average of 4°C or more, at the same time as cutting

energy use per home. Part of the long term increase of energy use for space heating lay on the increased heating volume due to building shell extensions (e.g. heated conservatories). In particular there has been a significant reduction in heating energy used in the last decade with reduction by a fifth since 2004 (Palmer and Cooper, 2013).

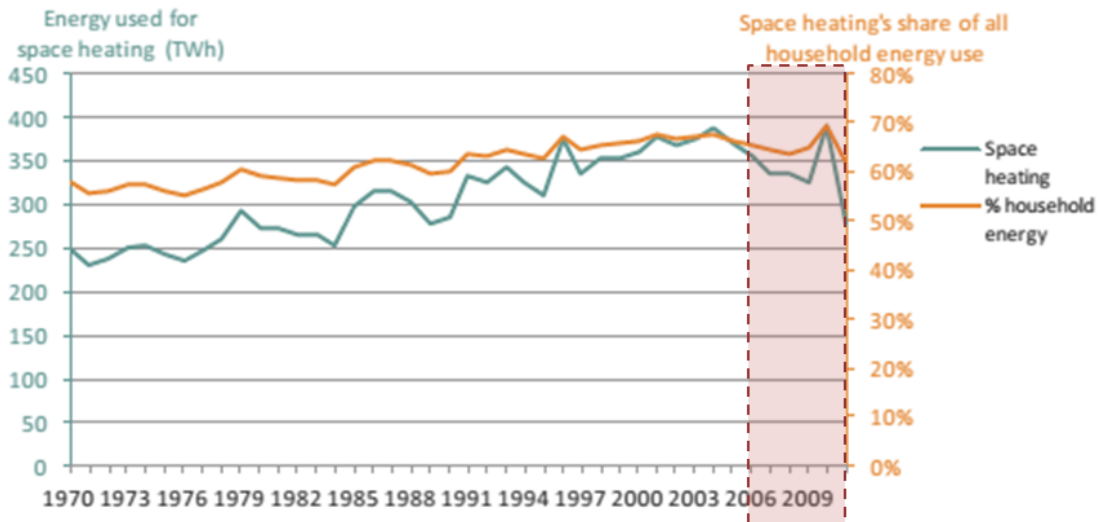


Figure 8: Household energy use for space heating (TWh) (source: Palmer and Cooper, 2013).

Despite an increase of more than two-fifths in the number of households since 1970 there has been a significant drop of one third in the UK’s energy use for hot water, mainly as result of the more efficient heating systems and improved insulation lagging of the water tanks and pipes (Figure 9).

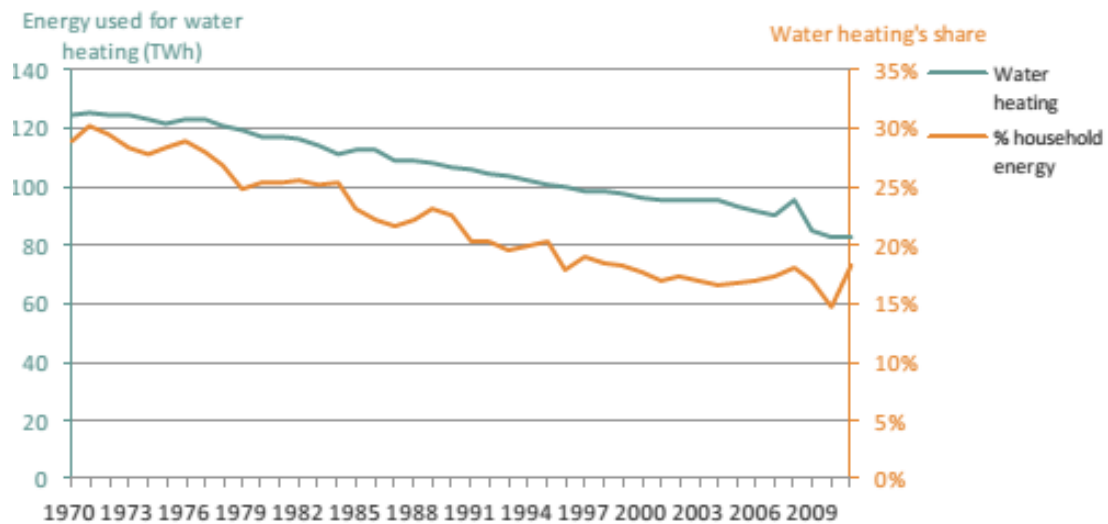


Figure 9: Household energy use for water heating (TWh) (source:Palmer and Cooper, 2013).

Thermal aspects of energy use are related to ‘heat loss parameters’ of the building - whether these involve heat transfer through the fabric (e.g. walls and windows) or heat loss due to air movement- from both deliberate ventilation and uncontrolled infiltration. Building Regulations increasing requirements effect directly insulation and airtightness levels both for new and refurbished houses. Insulation and airtightness improvements have the effect of reducing the heat loss parameter which is dependent on the age band of the building (Figure 10).

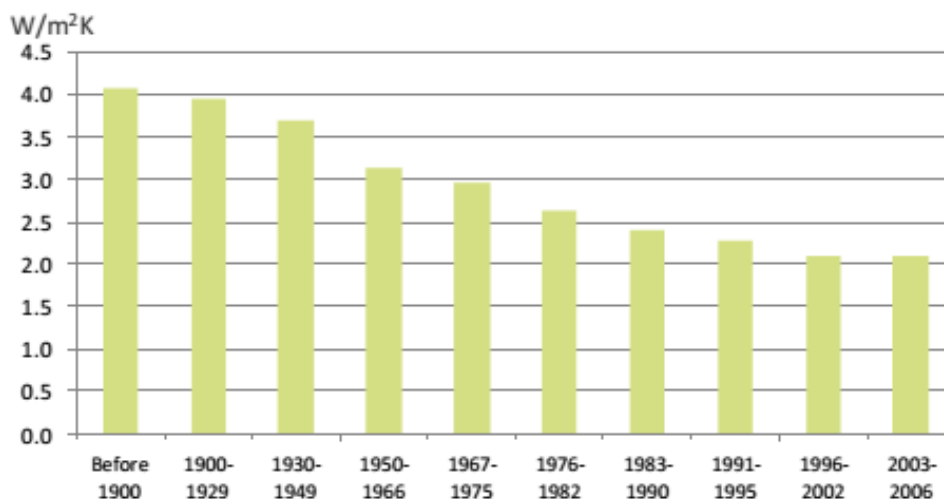


Figure 10: Heat loss parameter by dwelling age (2011)(source:Palmer and Cooper, 2013).

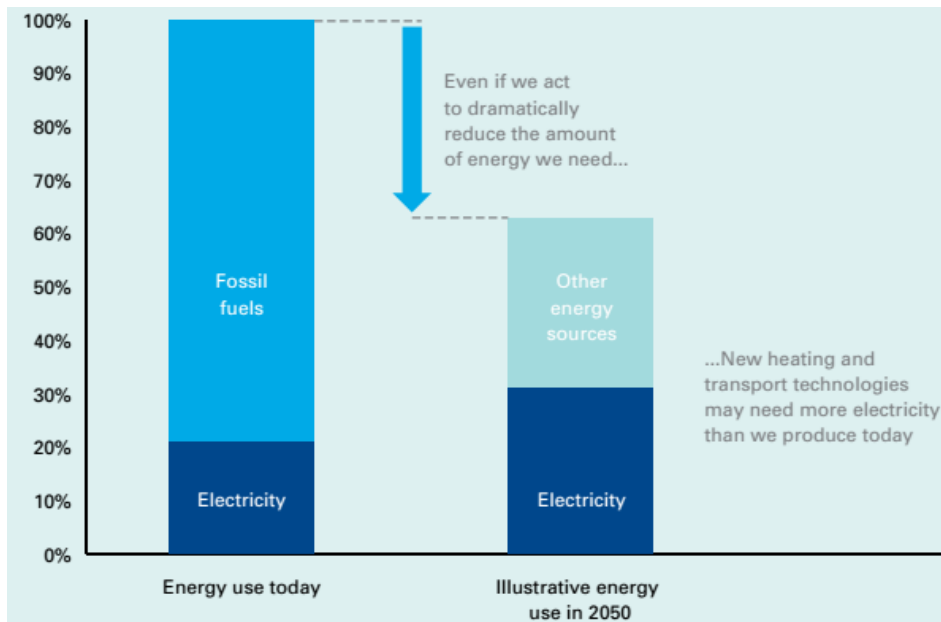


Figure 11: Projection of energy demand by 2050 (source: HMGovernment, 2009).

Future trends illustrated in Figure 11, show that electricity demand could increase, even as overall energy use declines along the lines of many (but not all) scenarios in which, more of the energy for heating and travel comes from electricity.

In this respect examples from empirical studies (i.e. Sorrell, 2009, Stevenson and Rijal, 2010) also suggest, that energy efficiency improvements in building fabric and (or) installation of low or zero carbon technologies can have different effects on energy consumption from those estimated or initially projected. As expected, the degree of these rebound effects can be difficult to quantify. Certainly a substantial contribution to building energy policy design requires more empirical studies to provide them with more significant socio-technical insights from policies' actual implementation. Policy frameworks in the domestic sector need to be considered under the lens of aggregated empirical studies that can assess their practical implication, from strategy implementation to use of the measure(s) in the household.

2.2 The UK's current social housing system

Social housing today is a significant part of the UK's total housing stock accounting for about 3.8 million dwellings (around 17% of all housing) despite the reduction occurring through sales, transfers and demolitions over the past two decades (DCLG, 2014d) (Figure 12). Over the last 30 years the difference between the number of social and private renters has decreased (Figure 13). The number of homes built in the social rented sector (including social and affordable rented homes) has also decreased between 2012 and 2013, falling to a 36% from 38,610 in 2011-12 to 24,550 in 2012-13 (DECC, 2013a).

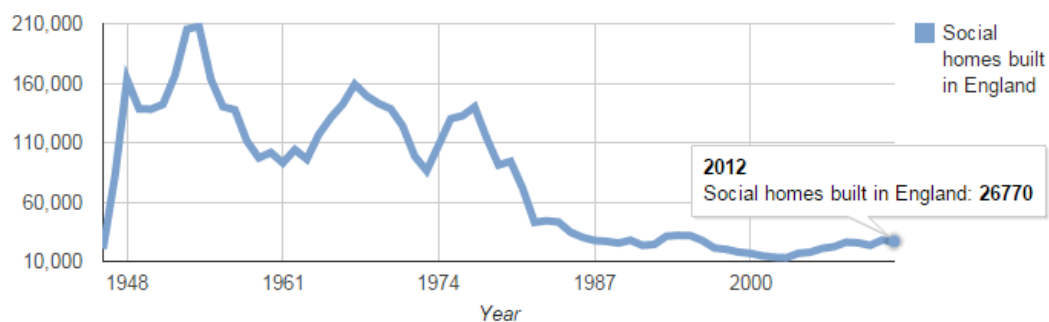


Figure 12: Historical trend data of social housing since 1946 to date in England (source: Shelter, 2014).

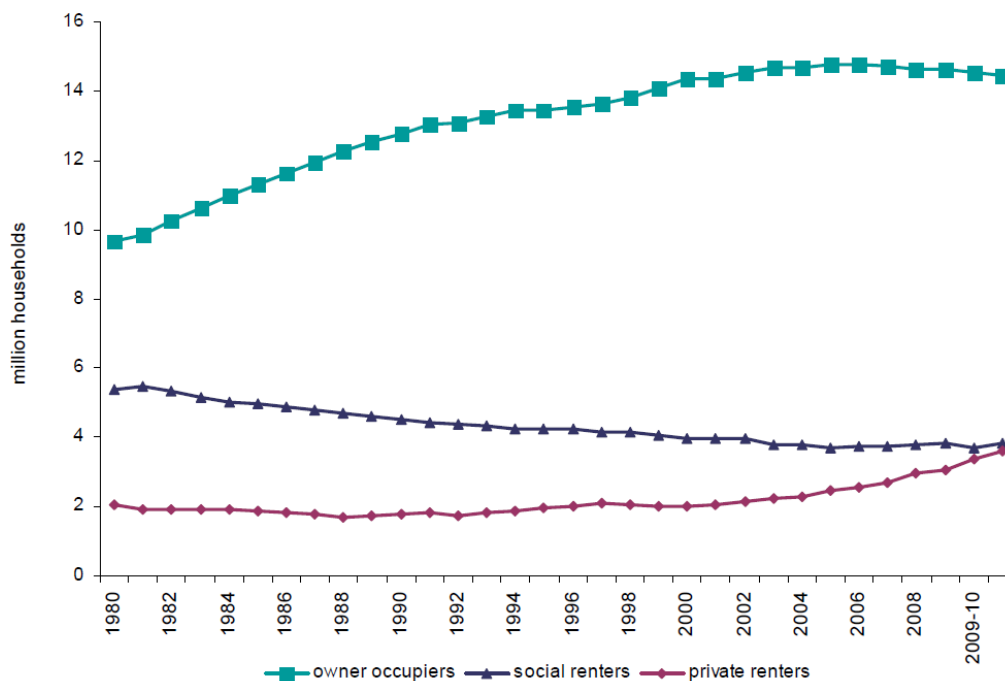


Figure 13: Trends between the three types of tenure from 1980 to 2010-11 (source: DECC, 2013a).

The current stock of social homes still remains largely managed by local authorities, councils and non-profit housing associations. It is split roughly equally between Councils and RSLs with 1.8 million owed by local authorities with 2.0 million owned by housing associations (DCLG, 2014c).

2.2.1 Socio-demographic trends

Social housing today provides accommodation to nearly four million households (17.5% of all houses). Most are people with vulnerability issues, homeless and some of them likely to be unemployed (by no means all of them of low income). Unemployment is high in the social rented sector (10% equating to 381,000 households in 2012-13) than in other tenures (6% of private renters and 1% of owner occupiers) (DCLG, 2014d), and also has a much higher proportion of 'other inactive' (26%) than the other two main tenures (DCLG, 2012b). From 1981 to date, social tenants' employment falling from 47 to 32% and full-time employment from 43 to 22% and almost a third of them (70%) are in the lowest quintile of household income. The figures in social housing also show that the level of social tenants with no educational qualifications is high up to 70%. This trend has been slightly aggravated by Right-to-Buy purchasers that have let a significant number of social housing units back to Housing Benefit claimants (63% of social renters were in receipt of Housing Benefit in 2010–11) or Councils/RSL (DCLG, 2012b, Greenhalgh and Moss, 2009, Stone, 2003). Most single parents (75%) and a smaller proportion of couples with dependent children (40%) receive Housing Benefit in the social rented sector (DCLG, 2012b). Around two-thirds (67%) of single person households aged under 60 in the social housing sector received Housing Benefit, around three times the proportion in the private rented sector (22%) (DCLG, 2011c). In the group of social tenants formally classed as 'unemployed', in the last decade there has been a significant rise in those groups classed as

‘other inactive’ of which 63% are single parents and in those reported as ‘permanently sick or disabled’ to nearly one quarter of all those of working age (Hills, 2007).

Compared to other types of tenure, family composition in social housing differs significantly. In social housing single person households are the most common (43%) (DCLG, 2014d) than in other tenures and 24% of all are aged 60 or over, which more than half are retired (Figure 14 and Figure 15).

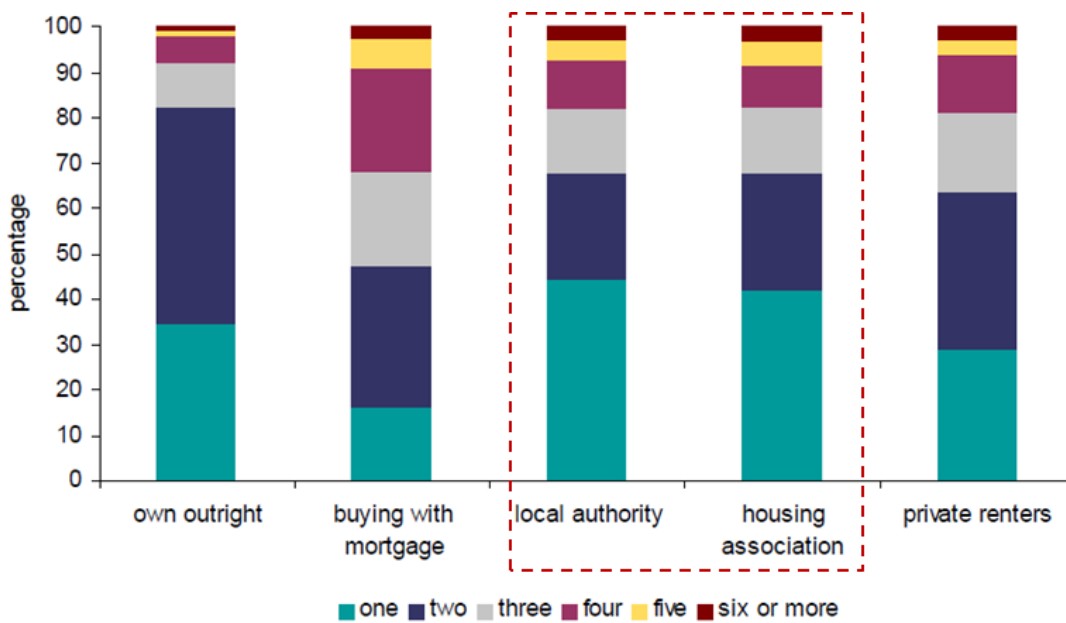


Figure 14: Household size (number of occupants) by tenure, 2010-11 (source: DCLG, 2012b).

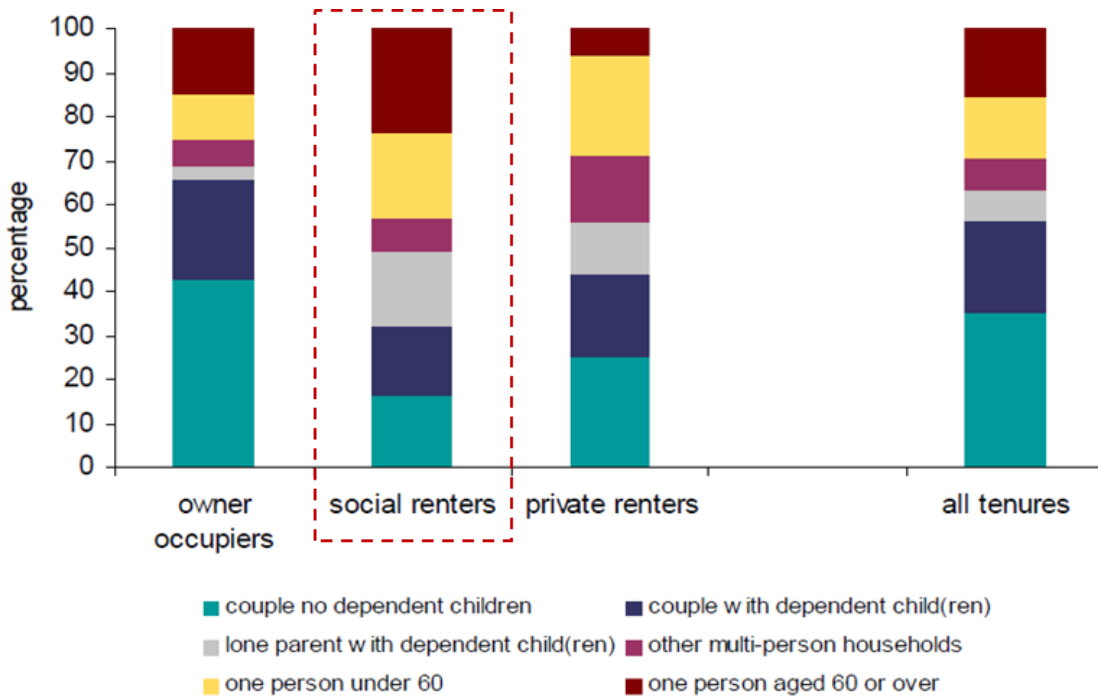


Figure 15: Household type by tenure, 2010-11 (source: DCLG, 2012b).

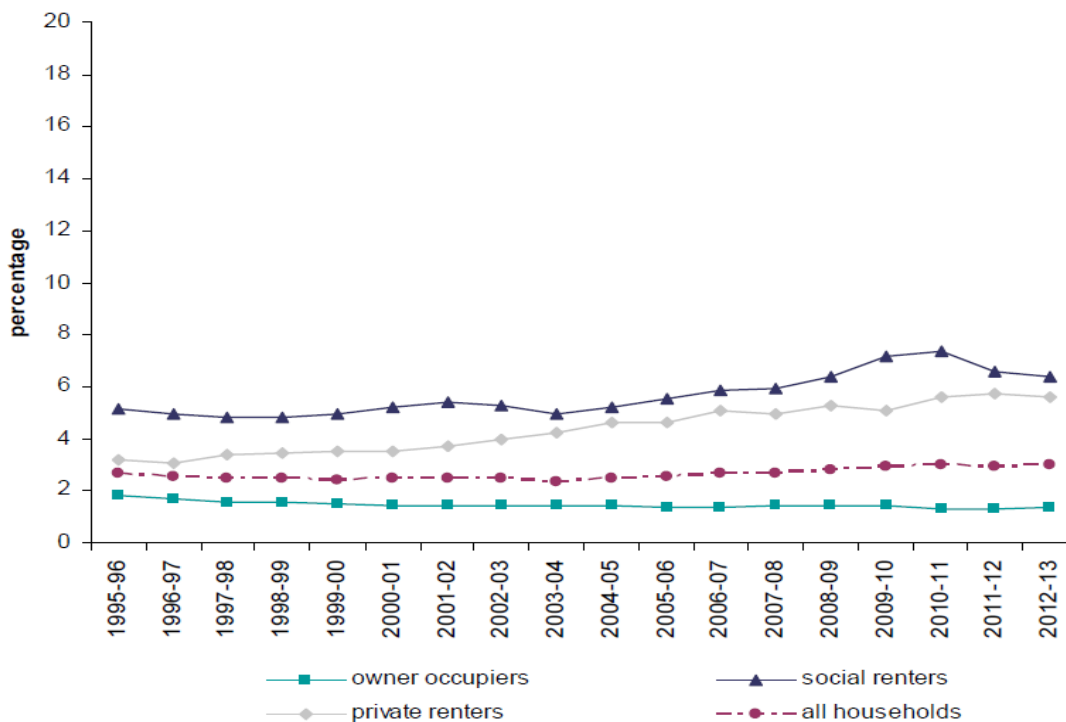


Figure 16: Overcrowding, by tenure type, from 1995-96 to 2012-13 (source: DCLG, 2014c).

There are lower levels of families with children (15%) and couples (17%), whilst compared with other tenures the greatest difference is in the prevalence of single parent

families (16%) with dependent children (DCLG, 2012b, Greenhalgh and Moss, 2009). The social rented sector also has higher levels of ‘overcrowding’ and ‘under-occupation’ compared to other tenure types, rising from 5% to 7% over the last ten years. Overcrowding is a problem that affects particularly households with children. The social rented sector has the higher levels than other tenures of children aged under 16 living in overcrowded conditions, 26.6% (DCLG, 2011a). However the findings from the latest English Housing Survey (EHS) show that overcrowding in the social rented sector has decreased from 7% in 2010-11 to 6% in 2012-13, Figure 16 (DCLG, 2014d).

The age distribution of social tenants is fairly even (Figure 17) with over a quarter (28%) over the age of 65 and almost evenly spread across the other age groups; whereas only a small proportion (5%) of social renters are under 25. There are also quite distinct ethnic groups within social housing tenure and since 2006 (Figure 18) the proportions have changed significantly. The largest proportion in 2012-13, in the population as a whole was 90% white and 10% ethnic minority households with the minority ethnic group decreased from 2006 levels (Hills, 2007, DCLG, 2014d, DCLG, 2011a). The average length of residence in 2012-13 was 11.3 years. Two thirds (62%) of social householders had lived in the current property for at least 5 years and 10% had been resident less than a year (DCLG, 2014c).

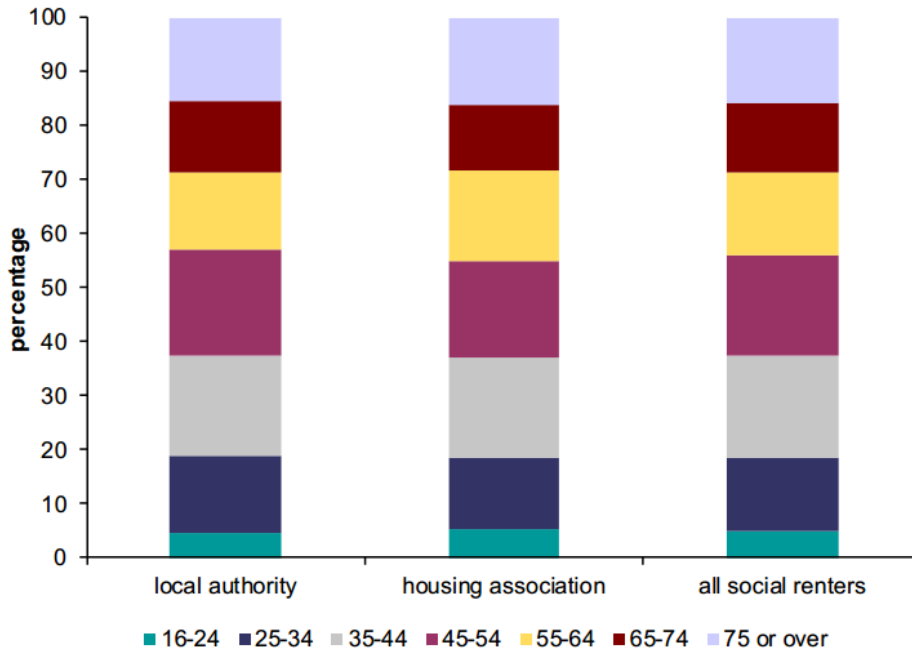


Figure 17: Age profile of social housing tenants 2012-13 (DCLG, 2014d).

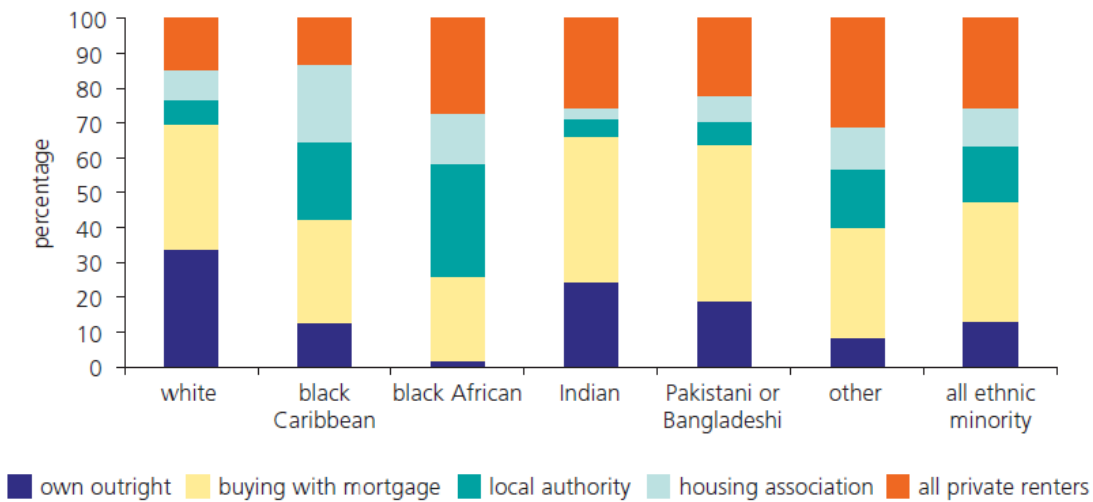


Figure 18: Percentages of households in social rented sector by ethnic group, 2009-10 (source: DCLG, 2011a).

2.2.2 Social housing physical context

This section discuss the physical condition and energy performance of social housing sector, as well as building characteristics like dwelling type, age, floor area, location, and finally the occupancy status, all of which can have a significant effect on energy use of the dwelling.

As regards physical condition, given that the large bulk of social housing was built before 1980, it is likely to require regular expenditure on a long term basis. Between late 1980s and through the 1990s to respond to issues of condition, quality and also to the demand for new decent council houses, the Government created a series of ‘regeneration’ programmes (Malpass and Murie, 1999).The purpose of these programmes post 1990s was to respond to the physical problems by different processes of refurbishment or demolition. The great majority of social housing met the target of Decent Homes Standard before its deadline December 2010 (DCLG, 2011d, DCLG, 2011a) whereas in 2012, 4.9 million dwellings (22%), as discussed in section 2.1.3, failed to meet the standard’s requirements.

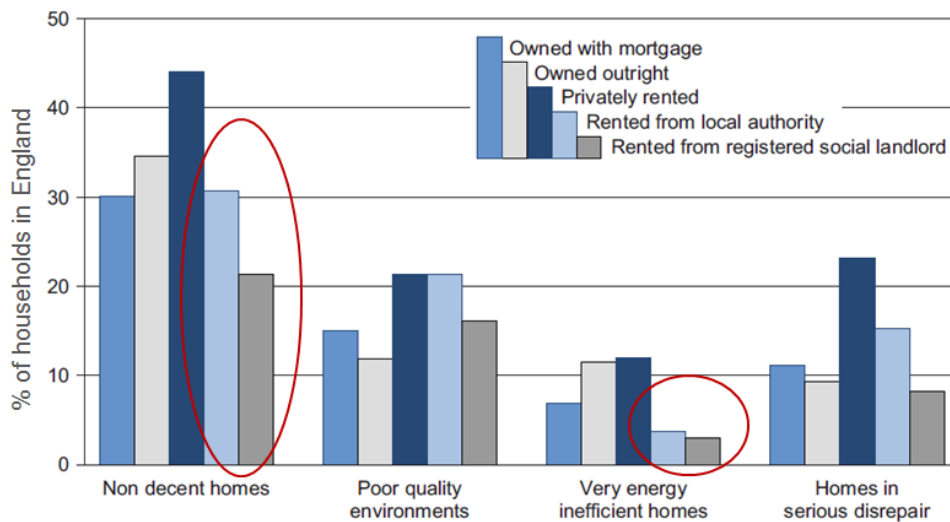


Figure 19: Poor living conditions⁹ by housing tenure in 2008 (source: Randall, 2011).

The percentage of poor living conditions in social renting households in terms of decent homes standards, poor quality environment; energy efficiency, or other serious disrepair conditions is lower than other tenures (Figure 19). The Decent Homes Programme forced many local authorities and other leaseholders into extensive repairs to the basic building fabric, which in many cases was well past its designed life (Greenhalgh and Moss, 2009). Although the number of non-decent homes in England continued to decline, in the recent

⁹ Poor living conditions include living in a non-decent home; having a poor quality environment; living in a home which is very energy inefficient; or is in serious disrepair.

years, there was a lower rate in meeting the Decent Homes standards (reduction of only 500,000 non-decent homes by 2007) as shown in Figure 20 (NationalAuditOffice, 2010). As already mentioned, the UK has one of the oldest and most diverse housing stocks in Europe. Despite weakness of energy efficiency performance into Decent Homes standards (e.g. compared to other standards such as Passivhaus, Table 2, p.61), their implication has been particularly effective especially for the dwellings built before 1980 based on the Part L building regulations requirements.

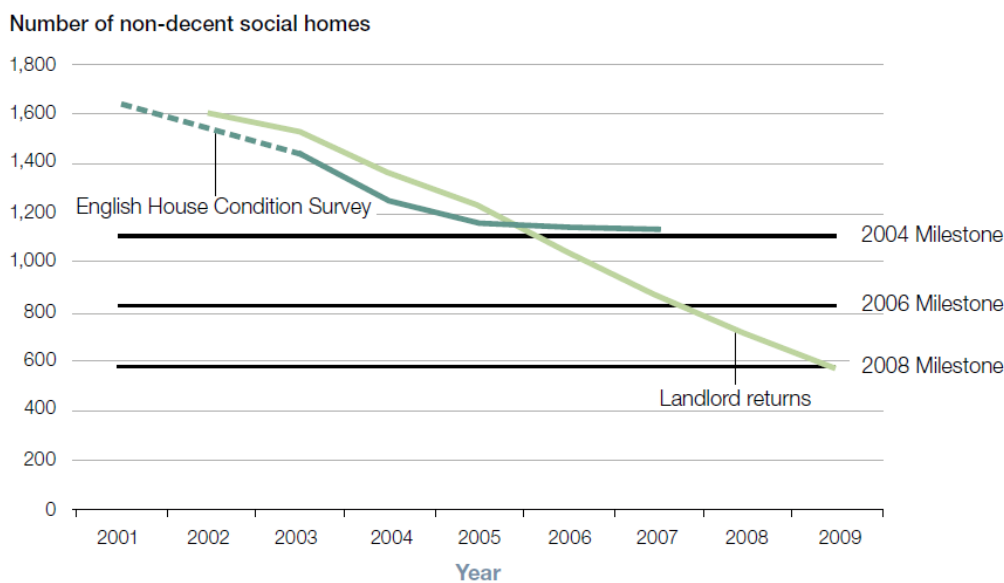


Figure 20: Progress in delivering Decent homes ins social housing (source:NationalAuditOffice, 2010).

The building age profile varies significantly across tenures (Figure 21) with three-quarters (73%) of local authority dwelling stock built before 1964, whilst the housing association sector has the highest portion of post-1990 dwellings (22%). Again similar variations between tenures can be found in the housing types (Figure 22); even though most of the total housing stock is made up of houses (81%), 37% of local authority dwellings and around 9% of housing association dwellings are low-rise purpose-built flats, followed by terraced houses and semi-detached houses.

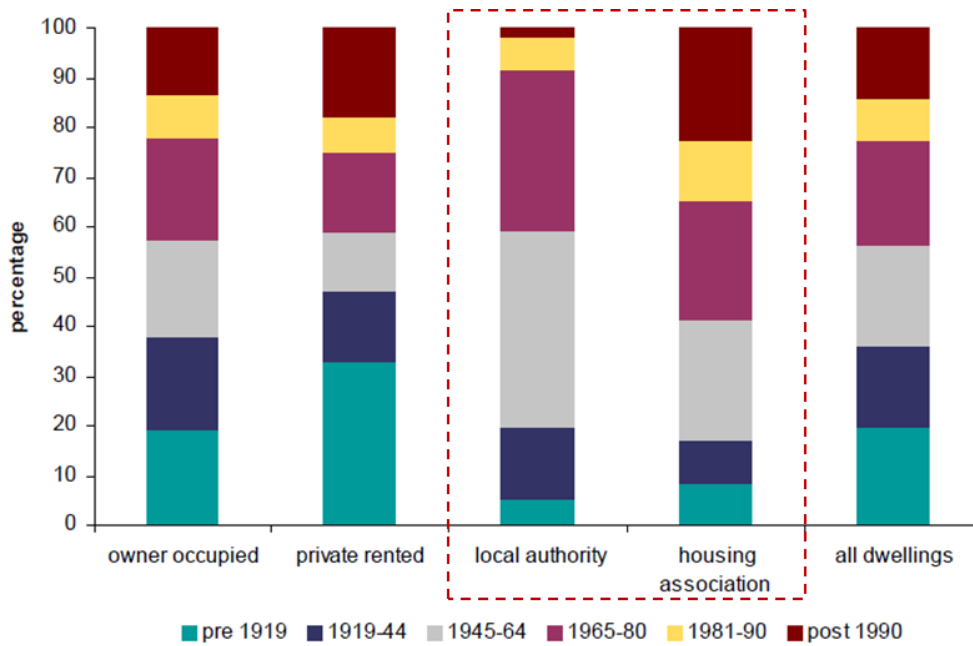


Figure 21: Age of housing stock by tenure, 2012 (source: DCLG, 2014c).



Figure 22: Percentage of dwellings by type and tenure 2010 (source: DCLG, 2014c).

As expected compared to other sectors, and in particularly to the owner occupied sector, there is generally lower total usable floor area; with more than two thirds (66%) of homes in the social sector having a floor area of less than 70m² (Figure 23) (DCLG, 2014c, DCLG, 2012b). Most local authority and housing association dwellings are occupied (91.3%) and located in urban centres and suburban residential areas. About the half of

social housing is situated in the 2nd to 5th most deprived of areas, as defined by the Government’s Index of Multiple Deprivation (DCLG, 2014c, Annex Table 10: Stock Profile 2012 :57).

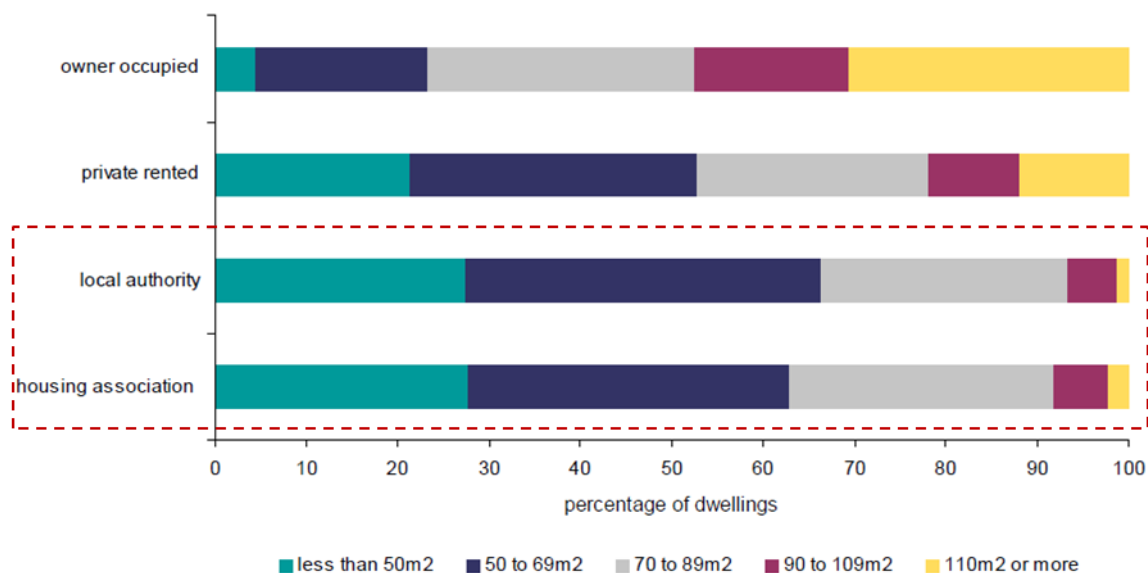


Figure 23: Usable floor area by tenure, 2010 (source: DCLG, 2011a).

As discussed in the previous section, the key ways to increase the energy efficiency of existing dwellings focus on improvements to heating systems and levels of insulation. Despite the poor physical condition of some of the current social housing stock, the social rented sector overall is more ‘decent’ than other type of tenures (Hills, 2007). This is because local authorities and housing associations have been more likely to invest in energy efficiency improvements than other sectors. Generally speaking, people who own their own homes are more likely to invest in cosmetic building improvements, such as better kitchens or bathrooms, rather than insulating the building or improving the heating (Palmer and Cooper, 2011). Housing associations and local authorities have a higher capacity in refurbish (and maintain) to stringent building standards, primarily focussing on reducing energy consumption cost than the private owners.

Since 1996, there has been a steady increase in the proportion of homes with central heating that in 2012 accounted for the 90.6% of all social housing. This is generally

considered to be the most cost effective and efficient method of heating (DCLG, 2014ap. 36). A further 9.8% had storage heaters as the main heating system, followed by about 31,000 dwellings with portable secondary room heaters. From 2005 less energy efficient boiler types have been replaced by the most efficient condensing boilers as new standards became mandatory for new and replacement boilers.

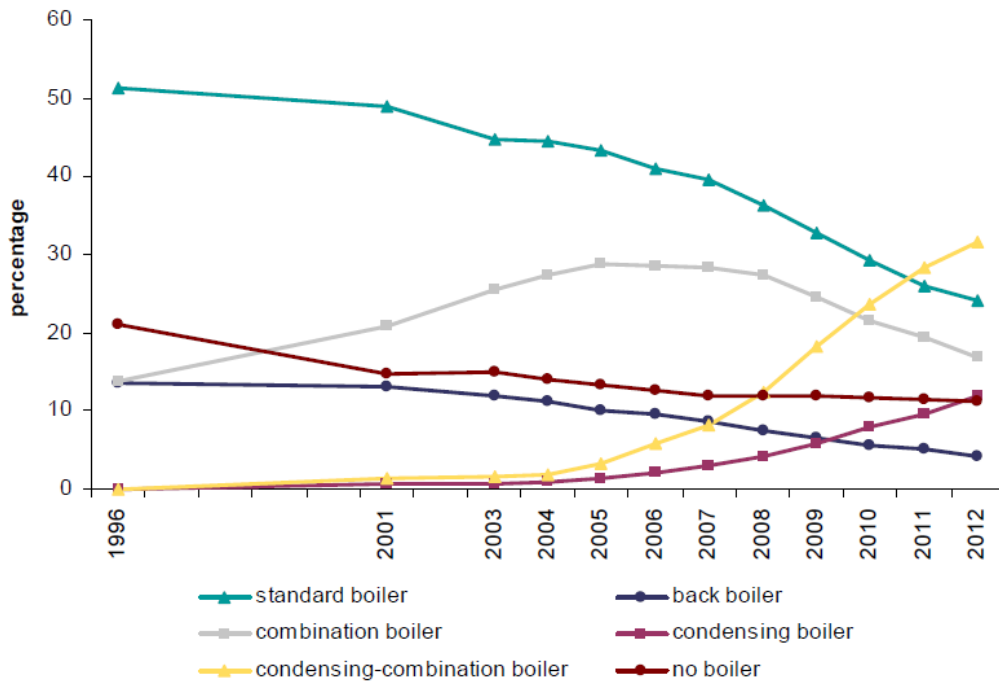


Figure 24: Boiler types in all housing stock from 1996 to 2012 (source: DCLG, 2014c).

The second key measure for improving housing stock energy efficiency performance involves insulation improvements to the building fabric (walls, loft and floor). The social rented sector has the greatest proportion of dwellings with cavity wall insulation, 200mm or more of loft insulation and full double glazing. In 2012, around 49% of social housing had cavity wall insulation with 27% having uninsulated cavity and 24% of other solid masonry, concrete, steel and timber uninsulated wall types), 34% had 200mm or more of loft insulation and 88% of full double glazing systems, Figure 25.

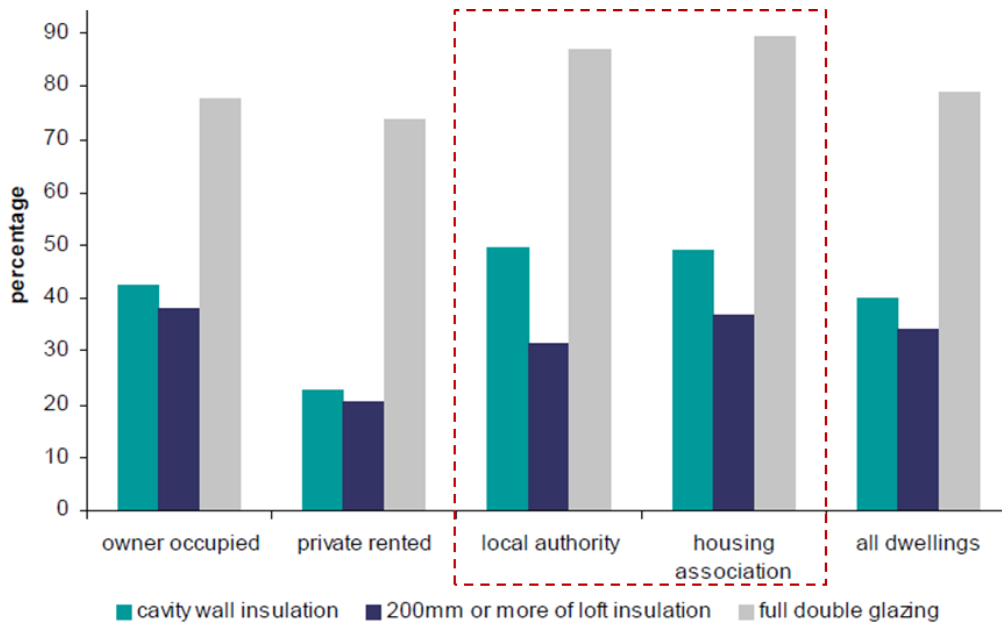


Figure 25: Insulation measures (wall, loft insulation and double glazing) by tenure, 2012 (source: DCLG, 2014a).

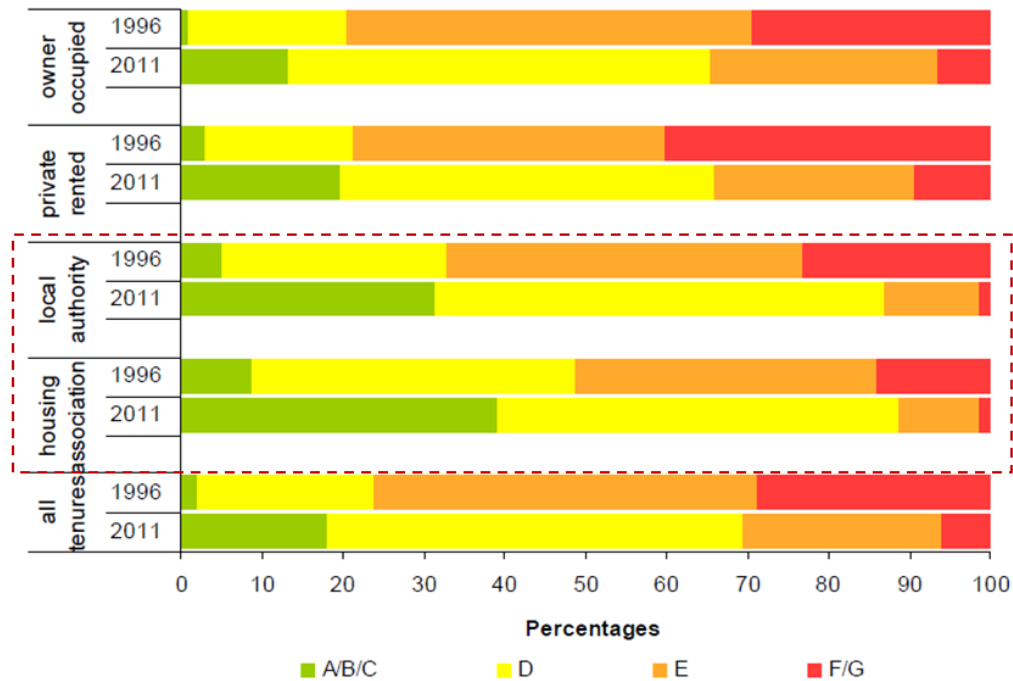


Figure 26: Energy efficiency rating bands by tenure type for 1996 and 2012 (source: DCLG, 2012b).

Based on the SAP rating assessments, between 1996 and 2009, the energy efficiency of the total housing stock substantially improved with an overall average rating increasing by 11 A points (from 42 to 53) (Figure 26). In the lead is social housing attaining the highest proportion of dwellings in the top A to C Energy Efficiency Rating Bands (DCLG, 2011a,

DCLG, 2011d). Nevertheless, this position of social housing efficiency also reflects the higher proportion of flats (Hills, 2007). Because of the Decent Homes standards for energy efficiency, the social housing sector in 2012 had the largest proportion of dwellings in bands A to C (39% of housing association and 32% of local authority dwellings); whereas only 1% of social sector dwellings were in bands F and G (down from 21% in 1996).

However, these energy efficiency assessments (e.g. SAP) and evaluations of energy efficiency intervention are often technical exercises in asset rating and overlook the human dimension and level that the householder's behaviour on energy use (Crosbie, 2006, Crosbie and Baker, 2010, Stevenson and Rijal, 2010). The factors affecting social housing energy trends and the current gap between estimated (assessed) and actual energy performance are discussed thoroughly in following chapters.

Summary and discussion

This section provides an overview of the context of low-carbon policies and the general policy frameworks for energy efficiency in social housing. It covers the current state of social housing including socio-demographic trends, technical characteristics and physical aspects related to its energy performance.

Over the last decades the role of UK's social housing has significantly changed and although it is decreasing as a proportion of the total stock, the social housing sector still provides accommodation to significant portion (17% , 3.7 million) of households in the UK. The need to retrofit existing homes is clear, and the social housing sector in particular has been suggested as a starting point for mass-retrofit schemes across the UK. The Government's intermediate (2020/2030) and long term (2050) visions foresee improvements in household energy efficiency, and policies and provide some additional financing support to vulnerable low income households and hard-to-treat properties in

social housing. The implementation of housing energy policies to date has been based on standards (e.g. Decent Homes) and assessment methods (e.g. SAP) that are focused largely on loft and wall insulation and central heating systems upgrades. Although the Decent Homes programme involved significant change to the landscape of the social housing sector, setting an energy performance benchmark, it focussed on delivering ‘typical’ refurbishment interventions. Other schemes like CESP, even though a ‘whole house’ approach was initially intended, were poorly implemented. Energy trends show that building improvements and energy efficient measures have cut energy use per home and provided better comfort levels by increasing internal temperatures. However there are criticisms that policies inadequately consider the interrelations between prices, energy efficiency and lifestyle changes.

Policies incentives for inefficient heating system replacement and insulation measures have been effective to a certain extent. Compared to other sectors progress has been made in implementing energy efficient measures in social housing. However, this appears as isolated measures in which ‘whole house’ interventions are overlooked. In this respect Government initiatives in funding refurbishment projects in social housing like the Retrofit for the Future competition programme show a tentative move to raise the bar, focussing on issues related to ‘whole house’ deep refurbishment interventions and of more stringent guidelines (e.g. Passivhaus Standards) and are explored in this study. Emerging issues in the implementation of deep low-carbon refurbishment in social housing are the subjects that this study intends to cover in the following Chapters 6, 7 and 8.

Chapter 3: Theories and approaches in domestic energy use

This chapter discusses the theoretical and empirical background of current energy use research. The main theories in household energy use and an outline of their main assumptions and (or) simplifications are discussed under the lens of their disciplinary perspectives. Technical approaches presented provide the context of physical dependencies in domestic energy use as explored in physics and engineering models. Non-technical approaches discuss the human dimension in domestic energy use from demographic, behavioural and socio-economic perspectives. Behavioural models and the different theoretical approaches (economic, psychological, sociological and educational) to interpret energy use behaviour are presented, focusing on the main theories used in the study's methodology. Socio-technical approaches follow considering combined technical and non-technical approaches. The building system, including occupant interactions and other 'whole-house' refurbishment and socio-technical considerations also discussed. The chapter finishes with an outline of the empirical studies and methods/tools that are used in current studies for systematic 'whole house' building performance and post occupancy evaluations.

3.1 Disciplinary viewpoints of domestic consumption

Previous studies (e.g. Stern, 1986, Lutzenhiser et al., 2010, Moezzi and Lutzenhiser, 2010) have focussed attention on the 'blind spots' of energy policies in residential energy use, often shaped by either (or both) overly-simple reliance on models and by data shortcomings. It is argued (Stern, 1986) that for understanding energy policy options it is 'important for a theory of energy use to be realistic in process' meaning that it needs to 'faithfully describe the ways individuals and organizations come to take the actions that add up to total demand'. To get a deeper understanding of actual household energy use avoiding 'blind spots' and 'user's black box' (Stern, 1986, Lutzenhiser and Shove, 1999,

Lutzenhiser et al., 2010) it is suggested elsewhere that there is a need for the combination of different research methods and theoretical traditions (Sovacool, 2014).

Energy consumption analysis 'is scattered across a variety of disciplines, and separated by distinct theoretical orientations and research methods' (Lutzenhiser, 1992). Different disciplines' perspectives and theories to household energy vary considerably as each envisions, emphasizes and includes (or excludes) different factors in the residential consumption system. Since the 1970s, energy research studies using different approaches, have offered considerations and theoretical explanations in either of the two main technical and non-technical (social) correlated entities in household energy consumption, both including often interrelated economic factors (Lutzenhiser and Shove, 1999, Sovacool, 2014, Stern, 2014).

The different as are distilled into four distinctive categories in Moezzi and Lutzenhiser (2010:209-210) based on the disciplinary objectives. The field of residential energy efficiency is approached through engineering/technology, economics, psychology, and sociology/ anthropology/ social studies of technology. These disciplinary approaches develop their theories with the main objective of understanding, explaining, interpreting and influencing variations of domestic energy use (Figure 27).

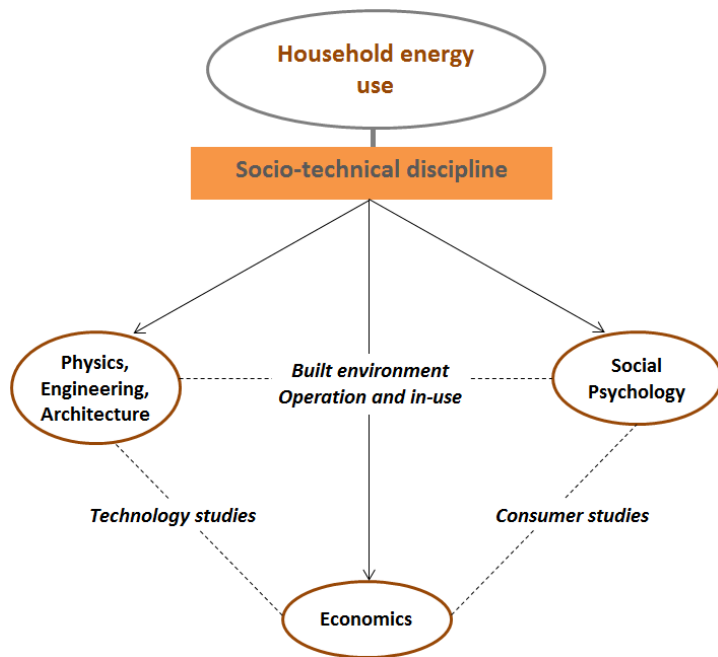


Figure 27: Links between a household's energy use and disciplinary approaches.

Engineering approaches, as the 'prime mover' (Moezzi and Lutzenhiser, 2010:209), explain energy use based on buildings' physical characteristics and on the ways the installed technology determines household's energy use. The engineer's focus is on the building's components, materials and devices; the objective is to understand end use by increasing efficiency, and therefore framed by strategies for implementation of energy efficiency technologies. Technological change may be incentivised by economics approach that from its disciplinary perspective sees energy use determined by price, income and consumer utility influenced.

Economics, as disciplinary approach, tries to understand and use prices as the main signal (or incentive) to influence consumer action. Consequently, its policy proposals focus on changing energy prices and those of efficiency technologies. The economics approach of individual decision-making and end-user's behaviours is a subset of theories from psychology, considering human motivation to be solely driven by economic factors.

Psychology's explanatory approach towards energy use allows for a wider range of individual consumption choices of the user (occupant). It looks at mental processes to understand and influence perceptions and actions related to energy use (Moezzi and Lutzenhiser, 2010:210, Table 1). As discussed in Moezzi and Lutzenhiser (2010), this disciplinary focus is on the understanding of individual perception and actions. The energy services desired there and the environmental impact, as well as cost, are approaches to motivating energy usage reductions and (or) more efficient products. Broader approaches to energy use are found in disciplines as sociology, anthropology and social studies of technology focussing on groups, cultures and society's larger social systems. These aim to understand patterns of variation and change in energy use from the social origin of these patterns and the sources of constraints and exogenous influences that shape consumption (Moezzi and Lutzenhiser, 2010:210, Table1). In a relatively large number energy use studies, the different disciplinary approaches of psychology and sociology are linked as social-psychology and not considered as two separate entities but as part of a broader social science category.

Although both technical and non-technical¹⁰ approaches make significant contributions to understanding household energy consumption, this bi-polarity of approaches raises significant constraints, as the determinants of energy use are seen as separated factors rather than co-determinants. On the other hand, this classical dualism of approaches, between the technical objects (materials/technology) and non-technical (occupants/users) recurs also within the same discipline. In sociology studies as described by (Warde, 2005:131-132), this 'disciplinary bi-polarity' generates 'either speculative social theories or detailed case studies', which in both cases offer a rather narrow understanding of

¹⁰ The term 'non-technical' is used in this thesis to describe the 'human dimensions involved in domestic energy use that include demographic, behavioural, socio-economic aspects related at both individual and non-individual level.

consumption. Combined interdisciplinary approaches, like socio-technical, tend to be more complicated and happen when are not solely driven by individual and radically opposed approaches. Although it can be sound rather acute and a strong defence of (Moezzi and Lutzenhiser, 2010:216), the statement that ‘the energy efficiency field has been left with rather limited means of debate and evolution’ might uncover the current need to step away from this discipline oriented-view. Hence to achieve socio-technical approaches in this field energy scholars need to: redefine objectively first their own boundaries of knowledge; establish a common language and patterns of communication among them; and see the application of their core theories from an objective view to identify integrated interdisciplinary pathways.

In the following section, technical, non-technical and aggregated socio-technical approaches and their variables will be discussed in more detail. It will also provide an exploration of how these theories are interrelated.

3.2 Technical approaches

Knowledge of household energy use and building performance has been often seen merely as a physics problem. The technical community has systematically investigated buildings at the level of their physical properties, focussing on buildings’ technical variations and on the efficiency and performance of materials, technologies of systems. Such approaches follow an environmental determinism which lies on the belief that the physical environment affects (or even causes) human social development towards particular activities. Considering that physical theories like heat transfer are well established are not further discussed in this section. This section focuses on the different approaches engineering models use and on the physical dependencies in households’ energy use emerged from previous studies.

3.2.2 Engineering and physics models

Traditionally, engineering and physics models use technical calculations based on principles of heat transfer theory (Hitchcock, 1993), looking at buildings' energy use from their energy flows and by using empirical relationships. However, technical changes affecting a building's physical parameters (size, materials, heating system or appliances) often may result in a change in its occupants' behaviour and both change its energy use. In several engineering approaches (e.g. Cramer et al., 1984:208, Steemers and Yun, 2009) considerations as such 'human attitudes, income, and intentions do not directly consume electricity rather, they influence how the physical devices are operated' (Cramer et al., 1984:208) are reasonably common. Despite the fact that the role of occupants (users) is widely recognized in such studies, households' energy use is seen more as a physical phenomenon related to technical specifications rather than a building system occupied and controlled by real persons. In most simplistic models buildings are seen empty of occupants or occupied by users/occupants with average (or 'default') behaviour.

There are two major categories of engineering modelling approaches: steady state and dynamic models. Steady state model approaches are mainly used for monthly or annual calculations using simple and robust equations of heat balance; however, they typically use major simplifications to model equipment and building fabric –related to behavioural factors– that have a direct or indirect effect on household energy consumption. A good example of this type of physics-based model for energy demand used widely in the UK is the Building Research Establishment's (UK) BREDEM model (Henderson and Hart, 2013). BREDEM algorithms can be easily modified, which has allowed a series of other heat balance modelling tools for UK housing stock (e.g. BREHOMES, BMT Johnston, UKDCM, DECaRB and CDEM) to use them as their core calculation engine (Shorrock and Dunster, 1997, Boardman et al., 2005, Natarajan et al., 2011). Dynamic models are

significantly more complex, looking at energy use variations on a short time scale (e.g. hourly). Two models widely used and market-placed energy simulation tools in the UK are the ApacheSim Integrated Environmental solutions (IES) and Passive House Planning Package (PHPP2007). Dynamic models allow investigation of building and systems performance in which thermal conditions related to indoor comfort and buildings energy use provide useful insights into the design stage of a building.

All these models, except for physical and weather driven variations in energy, cannot account for actual human practices (building system ‘in-use’) or issues related to the actual construction and application of technical measures (building ‘as built’). Especially in steady state models, there is a difference between the simulated performance of building’s fabric physical compounds or services (‘as designed’) and the ways these have been built (or installed) in the actual construction (‘as built’); with the latter, often fall far below estimated performance expectations (e.g. Sunikka-Blank and Galvin, 2012, Gupta and Dantsiou, 2013, Guerra-Santin et al., 2013, ZeroCarbonHub, 2014). Although physics models can be used to explore issues related to the ‘as designed’ and ‘as built’ differences data limitations on the ‘as built’ phase usually do not allows it (e.g. observations from measures and systems installation). In building-technology models the occupant is seen as a ‘physical entity occupying space, manipulating devices and contributing body heat to the indoor environment’ (Lutzenhiser, 1992:47). For example, a large number of studies investigating aspects of occupants’ interactions with blinds and lighting, window-opening behaviour, use of heating and air-conditioning systems and occupant presence are based on mobility or other physiological comfort related patterns. However, in most of these studies the understanding of human action or motivation is restricted as device-oriented engineers treat the human actor as a ‘body-in-motion’ (Lutzenhiser, 1992:47); and modelling an occupant’s presence based on unique time series with, where possible, realistic

approximations. Typically, in current simulation tools, the internal heat loads from human behaviour are based on usage and occupancy for every thermal zone. These studies assign occupant tolerance to indoor stimuli by modelling window opening and model appliances based on typical use patterns (Mahdavi and Pröglhöf, 2009, Page et al., 2007). Such approaches do not constitute sufficient understanding of the driving forces of the building system in-use.

Another difference between these models is the level of detail in the required input parameters for validating and calculating performance. These approaches rely on a representative sample of housing data at national level to estimate dwellings' energy demand in different scenarios. To obtain predicted values of a building's energy performance, modelling needs to be calibrated with actual measurements, which has its own serious constraints. The approaches to data collection can vary significantly, from a field survey to systematically collecting a large and consistent set of data regarding building occupants' presence and control actions (Mahdavi and Pröglhöf, 2009). For instance, demand forecasting models base their scenarios upon aggregated statistical data from housing surveys, often from demographic trends perspectives, dwelling size, average *U*-values, double glazing and different amounts of loft insulation, heating systems and types of micro-generation (e.g. BREDEM and SAP modelling assumptions). However, the main weakness of this approach is in keeping track of actual use. The lack of detail in data inputs leads to general assumptions that occupant behaviour can be modelled using occupancy schedules and patterns of self-conscious and rational actions based on 'average' or 'default' use choices. Some of these models (e.g. De Dear and Brager, 1998, Mahdavi and Pröglhöf, 2009, Summerfield et al., 2010, Natarajan et al., 2011, Yan et al., 2015) describe alternative approaches with higher levels of disaggregation, complexity to analyse the potential impact of various energy efficiency measures and policy scenarios on the

future energy consumption of specific housing stocks. Generally, as expected, physics models make a significant contribution to describing the physical aspects of a building system, but not people.

3.2.3 Physical dependencies in domestic energy use

Previous studies from engineering, architecture and building physics approaches in estimating buildings' energy demand, have examined direct and indirect¹¹ variables and physical parameters of the of building envelope (building fabric, type, size, heating and hot water systems, appliances and lighting) in relation to the fuel type (electricity grid, micro-generation) and climate. The aim of this section is to provide a literature review of these physical dependencies from previous research studies (Figure 28).

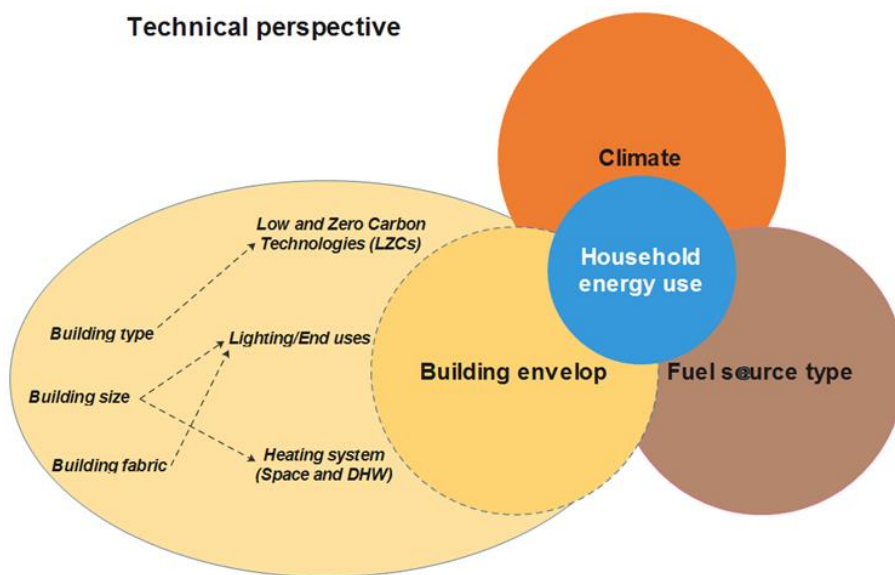


Figure 28: Technical perspective, dependencies in household energy use.

Variations in building characteristics, for example building type (e.g. detached, semi-detached, flat etc.), building size (number of rooms, area) and building age, have an important role in the performance of the building in large-scale household surveys and often fall in general classifications. In some cases where there is a lack of information

¹¹ These are physical variables that affect directly or indirectly a building's energy use.

about building fabric information, estimates can be used for building fabric components (e.g. glazing system, walls types, levels of insulation, loft and floors etc.). Dwelling size, as found in the study by Schipper et al. (1989), is a key determinant of household energy use, whilst building type appears to have a smaller effect. The influence of dwelling type on energy use varies across studies depending on the sample detail. In large scale household surveys classification is at the level of main categories (flats, detached, semi-detached, or terrace/end-of-terrace). If differences in area and performance between semi-detached and end terraces are not considered, this leads to potential misclassifications (Summerfield et al., 2006). A large number of studies (e.g. Yao and Steemers, 2005) of energy demand of UK domestic buildings is focussed on examining specific end uses, such as domestic hot water and space heating, and electrical appliances. Previous studies Steemers and Yun (2009) involved a comprehensive analysis and examination of building energy demand and found that, although heating degree-days is one of the most significant variables directly affecting household heating use, it is not sufficient to explain energy demand. Other significant physical drivers of household heating energy are heating type, age and size of the house, number of the heated rooms as well as climate; however, these are closely correlated with socio-demographic factors.

There is very limited evidence from current studies on the interrelations on dependencies of these factors and on how well energy efficiency measures can deliver energy savings in practice. A considerable amount of literature (e.g. Stevenson et al., 2013, Chisholm, 2014) debates the extent to which new low-carbon technologies can increase resource efficiencies to a level that allows the present patterns of energy service demand to become sustainable. In such approaches energy service demand (sufficiency) affects energy use as well as efficiency. The main weakness in this approach is the conceptual separation between means and ends (Shove, 2003b), creating dynamics of the unambiguous

relationships between efficiency and sufficiency which in practice entails ambiguous scenarios in policy agendas as discussed in previous section.

3.3 Non-technical approaches

Energy use is ‘not behaviour but an outcome of behaviour’ (Stern, 1992). It is determined by interactions between human and physical components, people’s presence in the building and by other actions that users take (or not) to influence the indoor environment and overall performance (Hitchcock, 1993, Hoes et al., 2009). From this viewpoint household energy use is highly structured by household composition/dynamics, status-appropriate dwellings and appliances, and lifestyle-based behaviour patterns (Lutzenhiser and Bender, 2008). In this thesis the term ‘non-technical’ is used to describe the human dimensions involved in domestic energy use that include demographic, behavioural, social-psychological and socio-economic aspects.

Although energy consumption was generally recognized as an important social problem, it was not until the 1980’s that the social sciences became interested in energy research. Social science perspectives see energy use as a human-based phenomenon focussing on the human aspects of the household related to economic and cultural factors. In several household energy studies (e.g.Hitchcock, 1993:153, Wilson and Dowlatabadi, 2007) occupant behaviour is seen from two distinct perspectives: use-related behaviour and purchase-related behaviour. The first focuses on the interaction of occupants with building’s physical variables, whilst the latter describes how building’s physical changes and purchases made by the occupant affect building’s overall performance and energy use. Compared to engineering perspectives, which are mainly oriented to technological design, or economics focussed on profit calculations, the contribution of the non-economic social sciences to energy offers the theoretical foundation for a consumption model in which energy and technology are the key mediators ‘between humans as social organisms and

their natural environments' (Lutzenhiser, 1992:54). From a social perspective, Guy and Shove (2000) argue that one of the reasons that energy efficiency of the building environment has failed to attract sociological attention stems from fact that there are no obvious theoretical footholds in building's technological design process often followed by amenable environmental and energy related invisible technical factors (e.g. insulation products considered invisible once installed).

One of the key approaches of social science research for explaining and predicting behaviours has been the development of models (e.g. decision making models in energy use). Such approaches in household energy use studies often include cultural, economic and psychological factors, modelling the human parameters of the household. Behavioural research models try largely to identify, for instance, the different types of energy use behaviour, such as conservers or spenders (consumption or demand behaviour) and the ways they affect energy use, focussing on the human needs and attitudes that drive energy demand. Although such approaches have shown that demand (or behaviour) is directly related to energy use, buildings' physical factors are generally purely considered (e.g. Hitchcock, 1993:155, Wilhite et al., 2000). Some of these studies become 'empiristic' approaches, in which behavioural variables are examined without providing a strong theoretical basis for variable choice (Bamberg and Schmidt, 2003).

In the 1990's there was an increased shift of researchers (e.g Gardner and Stern, 1996, Vlek, 2000, Fielding et al., 2010) towards theory-driven models that take into account or expand well established social science theories, such as in the altruistic behaviour theory of Schwartz (1977) or the planned behaviour theory of Ajzen (1991) (Cited in Stern, 2000). This offered the great advantage of models that can contain 'precise operationalizations of the theoretical constructs used and specify the causal processes through which they affect behaviour' (Bamberg and Schmidt, 2003:265). However, as

Stern (2000) highlights, the energy field now requires a move towards synthetic approaches of theories and models; that are capable of building links to other types of social theories, incorporating variables from more than one of their main classes, postulating relationships among them, and are able to explain significant behaviour patterns. Despite the pros of theoretical social frameworks established in behavioural models, researchers often come across the question of which model or social theory should be used (Bamberg and Schmidt, 2003:265). To provide a broader perspective on the main socio-theoretical and modelling approaches in energy behaviour studies, each of these is discussed in more detail in the following sections.

3.3.1 Theoretical approaches of energy behaviour

In contrast to technical approaches, social sciences have multiple theories to explain human reality related factors in energy use. Theories attempt to provide a general explanation of what happens in reality, whereas the models based on these theories to create a simplified representation of the actual processes that occur. Social-constructivism approaches, in contrast to environmental determinism, the focus is on an individual's learning that takes place because of their interactions. Social theories play the role of vocabularies in the analysis of domestic energy in behavioural studies and are:

...necessarily underdetermined by empirical 'facts'. As vocabularies they never reach the bedrock of a real social world, but offer contingent systems of interpretation which enable us to make certain empirical statements (and exclude other forms of empirical statements) (Reckwitz, 2002:257)

Chatterton (2011a), identifies four distinct types of social theoretical approaches in households' energy use summarised in Table 3 below.

Theories	Interpretation of energy use
Economic	Energy is a commodity and consumers will adapt usage in response to price signals
Psychological	Energy use can be affected by stimulus – response mechanisms and by engaging attention
Sociological	Modern energy use is largely invisible, energy systems are complex, and daily practices are significant
Educational	Energy use is a skill that is learned through experience in specific situations

Table 3: Different theoretical approaches to interpret energy use behaviour (Chatterton, 2011b).

Although each of these approaches looks at energy from a different perspective, focussing on different aspects of behaviour, there is a clear division on the ways they consider the individual. Economic and psychological theories see the energy user as an individual and behaviour as the result of his individual deliberation or decision. The individual decision of the energy user is based on the information and prompts available to them at that time (e.g. pricing structures or other forms of information subliminal or not). In this group of theories the set of individual choices is determined in a rational or semi-rational manner, and in similar ways to other individuals (Chatterton, 2011b).

Theories involved in such approaches are Ajzen and Fishbein (1980) ‘Theory of Reasoned Action’ (TRA) revised and developed into the ‘Theory of Planned Behaviour’ (TPB) (Ajzen, 1991). This theory was widely used in behavioural models and consumer behaviour studies (e.g. Krueger and Carsrud, 1993) and suggests that it is necessary to know people’s intention and what determines this intention in order to predict their behaviour. Although there are still unresolved aspects, there are relationships among three kinds of considerations attitude, perceived control and subjective norms, creating ‘an underlying foundations of beliefs about behaviour’ (Ajzen, 1991:206). The theory of

planned behaviour (TPB) has been widely used in decision-making models and in travel behaviour research (e.g. Anable, 2002), and pro-environmental behaviour studies (waste/water/energy) like Tonglet et al. (2004) study on recycling practices. In the household energy efficiency context, Fielding et al. (2010) explore attitudes and behaviours of Australian households expanding (Ajzen's) theory of planned behaviour model; their expanded version includes to (Ajzen's) TPB model variables such as demographic and household culture, descriptive norms and past behaviour examining their contribution to household behavioural patterns. However, although these theoretical considerations are useful to interpret relationships between decision-making structures in large data samples, they cannot be used to explain and organise elements of energy behaviour practices and user interaction with the building system of the empirical data that emerge from this thesis.

The second group consists of sociological and educational theories, which more emphasis on the context and structures that determine the ways that people behave, interact and do the things they do (Chatterton, 2011b). These theoretical approaches take the view that energy use is the result of a range of activities and 'practices' that different actors and objects are involved determining the processes that lead to how energy is used. Theories under this stream are cultural and practice theories and their different theoretical viewpoints to interpret and understand practices. Viewpoints from these latter theories are discussed in detail in the following section and were used in this thesis's methodology to interpret, organise and understand users' interaction with low-carbon interventions.

a. Cultural and practice theories

In social theories, cultural theories are founded upon a different form of explaining or understanding actions and social order. In the 1970's, social theories made an 'interpretative turn' to 'practice theories' or 'theories of social practices' in order to

understand the practices of ‘everyday life’ (Reckwitz, 2002:244). Set out this way, the concept of practice theory is considered by several theorists (e.g. Bourdieu, Giddens, Foucault, Taylor and Schatzki) as a type or subtype of cultural theory.

In practice theory the social is not placed in mental qualities, nor in discourse, nor in interaction but in ‘practices’ (Reckwitz, 2002:249). In the early formulations of Bourdieu (1976) and Giddens (1984) of practice theories, the approach to constituting and understanding the social realm focusing on the importance of seeing practices rather than signs or abstract structures. Over recent years, social theorists such as Schatzki and Reckwitz, inspired by preceding approaches, moving focused on everyday life of routines of body, mind, things (technology), structure and knowledge (Schatzki, 1996, Schatzki, 1997, Reckwitz, 2002), emphasizing the collective aspect of practices (Gram-Hanssen, 2009:154). A constitutive element in such concepts is that bodily and mental activities in social practices are linked with objects containing specific forms of knowledge, together consisting sets of routinised performances which in turn imply certain routinised practices (Reckwitz, 2002:250-255). Schatzki (1996), finds three main links between practices as formed by doings and sayings, and nexuses: through cognitive instruments such as know-how, through explicit rules and finally through teleoaffective structures¹². This last element (teleoaffective structures) according to his approach is necessary element for binding practices into useful sets (Schatzki, 1997:304, Gram-Hanssen, 2009:154).

Despite the development of such different theoretical considerations in social sciences streams, the term ‘practice’ is and has been used in a multi-various ways, often creating difficulties in delimiting its definition (Schatzki, 1996, Warde, 2005:136). Reckwitz (2002:249), sheds light on the conceptual meaning of the difference between ‘practice’ and

¹² A teleoaffective structure is a linking of ends, means, and moods appropriate to a particular practice or set of practices and that governs what it makes sense to do beyond what is specified by particular understandings and rules.

‘practices’ using the useful difference derived from the Ancient Greek between πράξις (practice) and πρακτική (practices)¹³ (examined in German between Praxis and Praktiken). He suggests that each single individual acts as a ‘carrier’ of practice which practice ‘represents a pattern which can be filled out by a multitude of single and often unique actions’ (Reckwitz, 2002:249-250).

Recent scholars, such as Warde (2005) and Shove and Pantzar (2005), have (re)introduced practice theory approaches into consumer and energy consumption studies. Although their approach slightly differs in elements of description and interpretation, they obviously draw on the work of both Schatzki (1996) and the way these are developed and discussed by Reckwitz (2002) (Gram-Hanssen, 2009:154, Gram-Hanssen, 2011:62). An increasing number of studies consider the potential of a revival of interest in theories of practice for the study of energy consumption (Warde, 2005:131).

However, practice theory approaches have been challenged in recent years by a number of different social scientists who fail to agree upon theory (Figure 29).

¹³ Practice (Praxis) in the singular represents merely an emphatic term to describe the whole of human action (in contrast to ‘theory’ and mere thinking). ‘Practices’ in the sense of the theory of social practices, however, is something else. A ‘practice’ (Praktik) is a routinised type of behaviour which consists of several elements, interconnected to one another: forms of bodily activities, forms of mental activities, ‘things’ and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge.

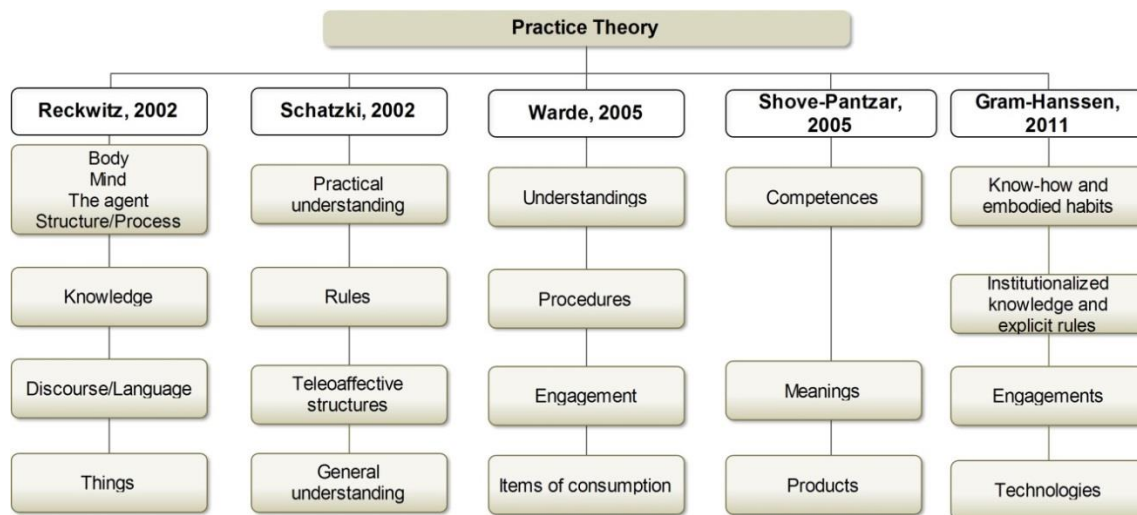


Figure 29: Different descriptions of the key elements in the understanding of practices (based on Gram-Hanssen, 2009:154, Figure1, Gram-Hanssen, 2011:64, Table1).

In the understanding of practice theories, and in the attempt to use practice theory for empirical studies, Gram-Hanssen (2009, 2011) compares the key elements that hold practice together in the work of the different scholars (e.g. Schatzki, Reckwitz, Warde and Shove/Pantzar). Even though different scholars may interpret and name various elements in different ways, the strongest disagreement arises from the question of how materiality, things and technology need to be incorporated in practice theory. So the role of technology has been debated by practice theory scholars. It has also been further developed (e.g. Shove, 2003a, Shove and Pantzar, 2005, Gram-Hanssen, 2011), to incorporate understandings from Science Technology Studies (STS) about how practices, norms and technologies are co-developed over time.

By aggregating the elements of these different theoretical considerations, Gram-Hanssen (2011) concludes that the most pertinent elements of household's practices are: the know-how and embodied habits, institutionalized knowledge and explicit rules, engagements, and technologies, adding that:

Practices are coordinated entities of sayings and doings that are held together by different elements and that are also what make practices collectively shared across time and space (Gram-Hanssen, 2011:64)

Another theoretical consideration in practice theory interpreting domestic energy consumption variations is the role of the individual (e.g. Gram-Hanssen, 2011, Morley and Hazas, 2011, Spaargaren, 2011). In this thesis, I adopt the approach of practice theory that does not have an individualized approach to practices. The individual is usually understood as part of a collective practice. However it is open to the individual, as a carrier of a practice, to change everyday life practices by variations in engagement and from the introduction of new knowledge or new technologies, (Gram-Hanssen, 2011, Gram-Hanssen, 2013).

3.3.2 Non-technical models

Social perspectives, using cultural and social models, try to understand the relationship between important aspects of social activities and energy use. Their concern is mainly focussed on the more symbolic nature of energy use structured by social consumption patterns and lifestyle (Hitchcock, 1993:154). The cultural analysis of consumption has frequently been reported in the literature as energy and lifestyle studies, in which lifestyles (cultures) are seen as the ‘recipes for living that differentiate social groups from one another’ (Lutzenhiser, 1992). Some socio-demographic and cultural issues, such as the family composition and members’ role in the household, different household work patterns or other symbols of energy use (e.g. increased energy consumption as an indicator of financial success), form the basic driving forces behind domestic energy consumption. Distinct groups of models in this field are the socio-demographic and socio-economic models, psychological models and other non-technical models shaped by different theoretical approaches to social drivers of energy use.

Demographic and economic models focus on household demographic characteristics and the economic systems. Some economic models use econometric (statistical) techniques to examine correlations between economic variables (such as fuel prices and income), demographic variables (such as the number of occupants, their age, employment status, etc.) and the ways these affect domestic energy use. Previous studies (e.g. Cramer et al., 1984, Stafford, 1985, Schipper et al., 1989), hampered by data limitations, the main concern was focussed mainly on the demographic variables considering them as the ‘crude indicators of cultural networks’ (Lutzenhiser, 1992:56) taking less into account their relation to purely economic factors and building’s physical parameters.

Psychological models use variables such as attitudes, values, norms and habits of the building occupants, related to cultural and contextual characteristics (e.g. physical infrastructure, level of information) assuming that these factors drive energy use. Their concern is about understanding the level and frequency of these variables and the driving factors of interaction that influences an individual’s or a household’s behaviour. Some studies (e.g. Becker et al., 1981) have examined energy use behaviour measuring both specific attitudinal factors directly related to energy use and more generally indirect related factors. However, although such studies identified some of the major attitudinal drivers of energy use (e.g. attitudes towards comfort and health), the process through which these attitudes affected energy use could not be determined. Other models (e.g. Brown and Macey, 1983) have tried to understand relationships between observed behaviour and personal and cultural beliefs affecting this behaviour. However, although they managed to identify how attitudes influenced behaviour, their effort were constrained again on directly correlate such considerations to energy use (Hitchcock, 1993:155). Previous studies (e.g. Kempton, 1986, Kempton and Layne, 1994, Darby, 2006) involved different types of information source (e.g. in social network of friends, family, neighbours or media) and

examined their direct effect on energy use. Two prevailing models in the context of social-psychology are the concepts of ‘social diffusion’ and ‘cognitive dissonance’; the first focuses on the flow of information and ideas through small social networks (communities, friends or work colleagues) and the latter emphasizes the ‘foot-in-the-door’¹⁴ information (Hitchcock, 1993:155).

Other important non-technical models have been formed from theoretical frameworks of knowledge of social constructivism and behaviourism. The observational study by Kempton (1987) on people’s behaviour which refer to heating systems examined how people assimilate and interpret information building up their own personal views: he called these ‘folk models’ and compared them with ‘expert’ knowledge. In Kempton’s study, the ‘folk model’ offers interesting explanations of apparently irrational behaviours. Environmental awareness (or perception) and its impact on energy saving practices has been largely discussed in previous studies. In Darby (2006) empirical factors of ‘tacit’ and ‘explicit’ knowledge, feedback and awareness on people’s behaviour in energy use are examined, whilst findings show that synergies between ‘expert’ and ‘lay’ sources of householder knowledge are required with or without the help of formal initiatives. In the following section key social and behaviour theoretical frameworks and conceptual approaches are reviewed and discussed.

3.3.3 Non-technical dependencies in domestic energy use

In previous studies (Lomas et al., 2006a) a great number of non-technical and behavioural factors are ‘interdependent’ creating confounding effects in understanding the drivers of household energy use. As such, socio-demographic variables are found indirectly to

¹⁴ The ‘foot-in-the-door’ strategies provide information that aims to motivate and encourage people feel and see themselves as very concerned about saving energy by acting in a certain way, believing in that sort of activity and freely choosing to publicly commit to reducing their energy use (*SHIPWORTH, M. 2000. Motivating Home Energy Action: A handbook of what works. Australian Greenhouse Office.*).

influence lifestyle choices and energy use. Socio-demographic characteristics with a strong influence on household energy consumption are: annual household income, home ownership (owner/renter status), ethnicity, and household composition (adults, children). However, there is no agreement across studies on the effects of age and number of children on energy use (Lutzenhiser and Bender, 2008:3-5). Research also suggests that energy consumption varies over the family lifecycle, between ethnic groups, and in terms of cultural practices (Lutzenhiser and Bender, 2008). Socio-demographic factors, such as the level of education and qualifications, in the study by Lomas et al. (2006a) found that although these are positively correlated with environmental awareness, the latter is negatively correlated with home energy use. Education acts both negatively and positively as is correlated to other variables like income affecting home energy use. Conflicting pathways of increasing or decreasing consumption partly explains why some energy savings initiatives do not deliver the expected results. Socio-demographic variables indirectly influence lifestyle choices and energy use. (Lomas et al., 2006a).

For demographic factors such as age and gender, their level of influence varies across studies. In the study by Carlsson-Kanyama and Lindén (2007), both factors are linked to other socio-demographic variables such as income and occupancy patterns, affecting household energy consumption via number and use of appliances (older occupants have fewer appliances more efficiently used), and time at home (women spend double the time compared to men). In other studies such as by Steemers and Yun (2009), the gender of the householder has relatively little impact on heating and cooling behaviours, whilst the age of the householder has the second strongest indirect effect on heating energy use, after income and followed by number of occupants.

Variables having a direct effect on household occupancy patterns are: the number of the occupants, time profiles (time of the first person getting up in the morning and the last

person going to sleep) and the household occupied period. The occupied period is directly linked to other behavioural determinants and usage patterns such as the frequency of use of appliances, and hence occupancy patterns influence a household's load profile (Yao and Steemers, 2005:665-666, Carlsson-Kanyama and Lindén, 2007).

Income is one of the key determinants of energy use in the long run (Schipper et al., 1989); but its impact varies substantially across energy demand studies (Lutzenhiser and Bender, 2008). In previous studies, notable associations have been found between physical parameters such as the type and size of house and income (McMichael, 2007, Lutzenhiser and Bender, 2008, Steemers and Yun, 2009); which in turn affect lifestyle and consequently consumption patterns (Carlsson-Kanyama and Lindén, 2007). In the study by Lomas et al. (2006a), interdependent factors are education, which is positively correlated with income; income, which is positively correlated with variables such as the product ownership; and product ownership, which is positively correlated with home energy use.

3.3 Socio-technical approaches

Despite the different of emphases between disciplines in defining the boundaries of complex physical and human characteristics in household energy use, there has been increasing recognition as Stafford (1985) argues that 'buildings per se do not consume energy; rather people living and working in buildings use energy', to the most recent statement of Janda (2011) 'Buildings don't use energy; People do'. It is broadly accepted now that to achieve energy use reductions, energy efficient interventions cannot perform at the desired standard without the occupant's (user's) cooperation.

A large number of studies approaches (e.g. Hitchcock, 1993, Hitchcock, 1995, Bordass and Leaman, 2005, Crosbie and Baker, 2010, Stevenson and Rijal, 2010) consider households as a system defined in both a technical and non-technical sense; and seen as 'a

complex technical and socio-cultural phenomenon which to understand this phenomenon, it must be viewed from both engineering and social science perspectives' (Hitchcock, 1993:151). The household consists of a combination of interacting human and physical systems and subsystems. It is the ways human activity is organized within physical infrastructure, which finally determines household energy consumption (Hitchcock, 1993, Leaman, 2005). The amount of energy the household system consumes is directly dependent upon the level of the different types of service (such as space heating, and hot water and lighting) required by the occupant and the efficiency with which these services can be provided. In this approach the main drivers of energy use are occupants' needs and behaviour, with energy use also determined by the building's physical characteristics (Hitchcock, 1993:153, Hitchcock, 1995).

It is recognised that 'social and technical phenomena must not be opposed', as 'the technical is socially constructed' (Joerges B., 1988:18, Latour, 2005). Both are 'society-shaping' (Hughes, 1987:51), and therefore need to be seen and analysed in conjunction (Palmer et al., 2006). A growing body of literature recognizes that household energy use is driven by socio-technical factors, whilst a large number of studies (e.g. Shove, 2003a, Heiskanen and Rask M., 2008, Morley and Hazas, 2011, Gram-Hanssen, 2013, etc.), consider how socio-technical systems may be shaped by sustainable consumption practices. From this perspective, this thesis argues the importance of overcoming previous deficiencies in separate technical and non-technical approaches. In the following sections, theoretical approaches are discussed in which technology and user are treated 'as a whole'.

a. Science Technology and Society (STS) approaches

Socio-technical systems approaches evolved from the science, technology and society (STS) literature along with a number of related approaches (Hinton, 2010). The mainstream perspective is to investigate direct and indirect non-technical (occupant/user)

and technical (building, technology) factors in household energy use. Physical infrastructures, things, people, habits, social norms and institutions, and their immediate physical and social context are considered as a system (Hinton, 2010).

There are three main theoretical approaches developed within socio-technical systems, differentiated in terms of how the links between society and technology are conceptualized. Actor-network theory (ANT) rejects distinctions between agency and structure recognizing people, machines and 'ideas' as interactional effects rather than primitive causes (Latour, 2005). Social construction of technology theory (SCOT) accepts that human actors shape technology (rather than human actions being determined and shaped by it), arguing that to understand technological use we need to understand first the ways technology is embedded and 'negotiated' (Klein and Kleinman, 2002) within its social context. While in the last approach, the social shaping of technology (SST), technological choices are shaped by multiple factors social, institutional, cultural and economic.

In this latter approach Akrich (1992), and Shove (2003b), argue that actions are 'scripted' to some extent by the technology with which users interact. Shove (2003b), referred to objects describes that their condition is largely prescribed by 'closed' or 'open' scripts (prescribed, prefigured or not). Other empirical studies have explored how 'scripts' are modified, adapted, subverted or misused in practice (Shove, 2003b). While, processes of familiarisation and adaptation, defined as 'domestication' of objects by Martinez-Gil et al. (2014), focused on the role and effect new devices have over existing technologies and practices.

b. User-centred theory approach

Alternative approach with practical application in the field of energy behaviour studies including in the built environment is Vischer (2008) 'user-centred' theory. Recognizing the difficulties in measuring human behaviour and the constraints in applying purely theoretical frameworks of social science in the practical context of planning, designing, building and occupying building environment, this theory tries to break the theoretical polarity between environmental determinism and social constructivism. In this theoretical framework, the building user's experience is central; and this centrality of the user as an operator, active agent, actor or consumer is a common element emphasized in all psychology and social theory approaches. However, although user-centred thinking is well established in such approaches, it is limited by the fact that 'no single overarching theoretical framework yet exists to create a coherent user-centred theory' (Vischer, 2008:234).

In Vischer (2008) approach, user-centred theory is defined by three key principles. The first accepts that the built environment exists to support the activities of users that it shelters, identifying who the user is and what experiences and activities they are carrying out in the building environment. The second accepts that user's experience is the route to learning about the building environment. In this respect, it defines what 'experience' is not by borrowing concepts from cognitive psychology, perception studies or 'subjective' considerations of conventional social science theories but from sophisticated qualitative methods that seek to understand the structures of the user's environmental experience. Finally, the third principle defines the building environment in relation to occupant (personal space, semi-private or shared space, social space etc.).

Focussed on the user's experience, this theory 'incorporates the interactive effects of both how occupants are affected and how they act on and respond to the environment' (Vischer,

2008:237). All buildings have users who are influenced by the spaces they occupy and who also act on them; the user is not a passive receptacle experiencing the built environment statically as input (Vischer, 2008:235). Such theoretical approaches can generate information on how people use and experience the built environment when they are employed in systematic empirical studies such as Building Performance Evaluation studies that are discussed in following sections.

c. Interactive adaptivity approach

Another integrated socio-technical perspective in household research (Cole et al., 2008, Stevenson and Rijal, 2010) is the ‘interactive adaptivity’ advocated by Cole et al. (2008). In his approach, the building is a dynamic and active complex system that forms a participatory process with interactive relations between occupants, and between occupants and building elements that can adapt to changing conditions; and which are capable of being responsive to social, ecological and economic conditions over time, maintaining their fluidity and robust design (Cole et al., 2008:333). In its inception, this approach considers that building occupants operate the building by interacting actively with building controls, technologies and systems to create their own microenvironment. Such approaches try to identify complex relationships between the technical assessments of physical performance (e.g. internal temperature, seasonal temperature change, or, on a larger scale, global climate change), with human behaviour analysis and then establish a concrete methodology that links system elements together.

Under the lens of adaptive approaches of the occupant/user in the building environment, adaptive thermal comfort theory is also discussed. First proposed in 1970s, this theory uses the fundamental principle as expressed by Nicol and Humphreys (2002:564) ‘if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort’. Under this definition, the adaptive approach accepts that people are not inactive

recipients but have a natural tendency to interact with their environment using numerous strategies and adaptive approaches to achieve their own thermal preferences (Nicol and Humphreys, 2002, Zhanga et al., 2010, Liu et al., 2012a). In this there are three main types of adaptations: physiological, psychological and behavioural.

Physiological adaptation usually considers any thermal changes in regulating the human body in response to the environment. Although this type of adaption is less studied than the other two (psychological and behavioural), it is considered as the most significant factor in explaining variations in perceived and predicted thermal sensations and acceptability (Liu et al., 2013:10). Most of the current studies exploring this area are focussed on experiments on adaption of the human body within a climate chamber. There are fewer studies that have explored physiological responses in real environments, focussing on variations of physical thermal parameters on occupants clothing preferences and activity levels (Liu et al., 2012a:313).

Behavioural adaptation in comfort can be better studied by observations in the context of real environment. This type of comfort adaptation includes conscious and unconscious behaviours performed in an occupied environment. It consists by three categories: the personal adaptation (e.g. clothing layers), technological (e.g. control over heating and ventilation devices) and cultural responses (e.g. sleeping with the window open). Occupants' adaptive behaviour has been considered as a dynamic process in which the frequency of behavioural adaptation is affected by various factors such climate, culture and economics, as well as the level of availability/accessibility of control they have over the technology or through regulatory actions and in relation to the individual characteristics and the occupants' thermal background experiences (Liu et al., 2012a).

Psychological adaptation is the most complicated as it composes characteristics that cannot be easily described or evaluated. This type of comfort adaptation is affected by occupants' perceptions of comfort, their perceived environmental control level and the ways these were determined by their subjective past thermal experiences and thermal expectations. Previous studies have shown positive relationships between perceived environmental control level and occupants' thermal comfort and satisfaction (Williams, 1995, De Dear and Brager, 1998, Liu et al., 2012b).

3.4 Socio-technical energy studies in housing

The main barriers to more comprehensive understanding of socio-technical factors lies in the fact that 'relatively little attention has been given to systematically analysing and reporting the respective effects of those factors' (Lutzenhiser and Bender, 2008:191). In some cases STS are 'largely invisible, or rather, they are such an integral feature of modern life that their role can be overlooked' (Graham and Marvin, 2001; Hinchliffe, 1996, Cited in Palmer et al., 2006). Consequently our understanding has often been 'hampered by a chronic shortage of detailed energy use data matched to descriptions of the house, the occupants, the internal conditions and the installed services and appliances' (Lomas et al., 2006b).

There are two main categories of energy studies investigating how socio-technical factors influence energy use in houses. The first category includes studies that employ socio-technical approaches in large samples. This often involves either monitoring or energy modelling (or both) and analysis of socio-technical factors at the household level using data based on:

- Energy use based on utility data;
- Buildings' technical characteristics based on survey data (size, type and age); and

- Social characteristics based on demographic survey data (household composition, income, ownership etc.).

Research monitoring and modelling socio-technical aspects in domestic building in the UK, includes the longitudinal monitoring project involving several hundred UK homes carried out by Carbon Reduction in Buildings (CaRB). The study has developed socio-technical models (CaRB BBN) of energy use underpinned by the data from extensive monitoring; these investigate which of the socio-technical variables or combinations of those has the greatest impact on home energy use, as well as the size of this impact. Another similar research approach using smaller sample is the Riccarton Ecovillage and Living Laboratory. A 20-household newly built village at the main campus of Heriot-Watt University in Riccarton has been employed in order to model a range of scenarios and usage patterns looking more specifically at the combinations of electricity usage schedules that minimized dependence of energy supply (Hawasly et al., 2010).

However, one of the main limitations of such samples is the level of detail (quantity and quality) of data obtained, affecting significantly the level of analysis that can be achieved. The poor quality of inputs entails general assumptions where, for instance, occupant behaviour is assumed to follow static or average occupancy schedules. Studies based on such large samples are certainly not developed to explore occupants' actual use or interaction with a building's technical parts, nor are they designed to zoom in on socio-technical factors such as the number of occupants, their presence, and heating systems usage. The level of disaggregation in most of these approaches is orientated towards the average technical and social factors (e.g. building type and household income), in which the analysis of direct (or indirect) correlations between these variables and their influence in energy use (e.g. heating energy consumption) relies heavily on quantitative statistical

associations and is used to analyse the potential impact of energy efficiency measures and policy scenarios.

Under the lens of an integrated socio-technical perspective, the second category includes studies based on smaller samples employing more detailed analysis based on empirical evidence and focussed on the nature of the practices of everyday energy use in households. Empirical studies in such samples (e.g. Stevenson, 2004, Gram-Hanssen, 2010) attempt to link user behaviour to building physical performance. Some have more emphasis on developing methods and techniques of evaluation, others are focussed merely on the theoretical context they have chosen as the base of their empirical analysis and interpretation or attempt to combine both.

Even though these studies reveal important technical and behavioural aspects of energy use, they render difficult to understand and embrace the way all different actors take part in the actual practices. This limitation stems from the lack of consistency in their methodologies and in the formalization of techniques (Crosbie, 2006, Gram-Hanssen, 2010), called by (Meir et al., 2009) a lack of ‘methodological canonization’. The size of these empirical samples which falls below 50 cases, does not allow quantitative conclusions about users’ behavioural practices for broader demographic groups. However, that said, they offer significant indications from practical insights into occupants’ behaviour, that allow us to gain knowledge about ‘the sources of variation of current household energy use which remain largely unknown’ (Moezzi and Lutzenhiser, 2010). In several studies (e.g. Socolow and Sonderegger, 1976, Sonderegger, 1978, Schipper et al., 1989, Hackett and Lutzenhiser, 1991, Lutzenhiser and Bender, 2008, etc.) involving smaller samples of identical units with similar physical conditions and occupied by demographically similar families, large variations (often extreme) between households’ energy use have been found. Another example of this can be found in the recent study by

Gram-Hanssen (2010), which provides insights into families' differences in practical understanding, embodied habits and know-how of residential heat comfort practices, and reveals significant variations in the usage of radiators and openings.

In this respect, there is an emerging body of empirical research (Gupta and Chandiwala, 2010, Spataru et al., 2010, Stevenson and Rijal, 2010) involved with Building Performance Evaluation (BPE) methods and occupant feedback techniques in smaller samples in UK new or refurbished domestic buildings. This type of research takes various different perspectives on the evaluation of multiple socio-technical factors in a small number of housing units. The methods used are often based on household cases and evaluate socio-demographic factors, technical aspects and occupants' interaction with the building environment and systems, such as ventilation, heating and appliances.

Drawing upon the empirical literature on household energy consumption, some general problems in the socio-technical approaches are found in the following areas:

- Practical constraints on the data type and collection (e.g. size, sample characteristics, methods, means of collection being qualitative/quantitative, cost etc.);
- The multi-disciplinarity of socio-technical influences on energy use often leads to different methodological and theoretical structures in their approaches, giving different weight to the variables being dealt with (Moezzi and Lutzenhiser, 2010) (e.g. samples evaluated by models based on social perspectives undervaluing technical variables involved in energy use); and
- The different level of detail and disaggregation of each of these methods, ranging from the collection to analysis of data (e.g. BPE methods or practice theory analysis etc.).

Despite the attempts of data-harvesting of the first category studies, the quality of data collected and accessed is still low and sometimes rather poor. These barriers result in what

Lomas et al. call the current ‘lack of understanding about the interaction of social and technical factors’, meaning that ‘conventional domestic energy models cannot reliably predict current and likely future domestic energy demand’ (Lomas et al., 2006a). Despite very little systematic empirical work having been done over the past two decades that combine people’s behaviours, buildings, equipment, lifestyles and their interactions to identify how these actually result in energy flows and emissions patterns, there is currently a growing number of empirical research studies in the UK involved with monitoring retrofitting case studies.

3.4.1 Building system and occupant interaction

As explained in previous sections, in building energy use studies scholars (e.g. Stern, 2000, Palmer et al., 2006, Cole et al., 2008, Lutzenhiser and Bender, 2008, Mahdavi, 2009, Meir et al., 2009) often use the notion of ‘interaction’ to describe interrelated processes between technical and non-technical factors related to building energy use. In many cases, the term is used to include different behavioural factors (e.g. attitude, habit, lifestyle, knowledge etc.), routinised control practices and building systems. In my study the term interaction includes all the aspects of ‘practice’ (Praktik) (Reckwitz, 2002:249), in which the occupant(s), through his presence, routinized behaviours and control oriented actions related to buildings' environmental systems, affects the building’s energy use.

According to Bluysen (2009:201) there are three types of interaction taking place in the building environment: interactions at the human level, interactions at the indoor environmental parameter level and interactions at the building level. The interaction at the building level is defined by the interactions between different elements of the building and between the building and the environment. This is the type of interaction on which this thesis is focussed. These interactions influence occupants’ wellbeing, health and comfort and determine occupants’ interaction with the building.

3.4.2 The ‘whole-house’ approaches

There are two common energy efficient approaches to house refurbishment the ‘measures-based’ approach and the ‘whole-house’ approach. The former approach involves the installation of energy efficient improvement measures one-by-one at different times; whereas the latter involves the installation of a package of energy efficient measures (building fabric, building services and systems) that occur simultaneously.

A ‘whole-house’ low-carbon approach, which was undertaken in the RfF sample, implies that the household’s needs (energy demand) and impact (carbon emissions) are seen as a whole. Although such approaches include a range of measures from cost-effective energy saving schemes to renewable heating and electricity measures, and improvements of the building fabric, there is little evidence yet showing how this ‘whole-house’ approach is able to deliver radical energy savings in practice, taking into account the householders (human factor). Measures’ efficiency when defined from a purely subjective policy perspective, resting largely on their physical criteria, often confirms arguments as such ‘more efficient’ does not mean lower energy use (Moezzi and Diamond, 2005). In the current policies, involving ‘whole-house’ approach, ‘user’ factor is often either vaguely implied or even not considered. This thesis accepts that in a ‘whole-house’ approach, the user’s experience with a building system as a whole needs to be measured of its actual effects and effectiveness by systematically and empirically study together low-carbon and ‘whole house’ refurbishment interventions with user’s/occupant’s interaction.

3.5 Building performance approaches

Actual and real-life performance of buildings often fails to reach design and estimated expectations. People and processes involved in making visible buildings actual performance often, as Bordass (2001:15) puts it, are ‘flying blind’. Design targets set at the whole building level (e.g.: total heating consumption kWh/m² per year), although they

provide technical design freedom, often in practice are not always effective in delivering energy efficient buildings (Bordass et al., 2001). The cause of this is the assumption about how the individual features contribute to achieve (or not) the target, which here are real occupants, which cannot be verified until long after the building has been occupied.

Processes that serve to decrease the distance between estimated and actual performance, and hence between design and use, require ‘examinations of the effectiveness for human users of occupied design environments’ (Zimmerman and Martin, 2001:171). Despite the different scientific approaches, this description given by Zimring and Reizenstein (1980:429) offers the broader useful working definition that describes the grounds for the Post Occupancy Evaluations (POE). Advocated by Zimmerman and Martin (2001:171) perspectives which recognize that:

When the goal of projects is to implement innovations and has specific goals for changing behaviour, an evaluation to assess whether these objectives are met is essential, and typically a pre- and post-evaluation is recommended.

The rapidly expanded and diverse context of POE studies ranges from low/high-rise housing, commercial offices and public buildings, to academic institutions and city parks (Zimring and Reizenstein, 1980). The context and implementation of these studies in buildings is discussed in the following sections.

3.5.1 POE studies on buildings

Processes involving ‘systematically comparing of the actual performance of buildings, places and systems to explicitly documented criteria for their expected performance’ (Preiser and Vischer, 2005:7) define BPE studies. The most sustained methodological attempts to building performance evaluation have established the Post Occupant Evaluation (POE) process. POE’s have been viewed as part of the BPE’s process and ‘tool’ that evaluates ‘buildings in a systematic and rigorous manner after they have been

built and occupied for some time' (Preiser and Vischer, 2005:8). However, to some extent, POE differs from other building performance evaluations, technical tests and physical inspections as it focuses on the requirements and experiences of building occupants (users) including aspects as such health, safety, security, operation (functionality and efficiency), aesthetic quality, psychological needs, comfort and satisfaction perceptions. But most importantly compared to other BPE studies, it has progressed towards emphasizing a 'holistic' and 'process-oriented' approach in building evaluation in which building's aspects are not taken aside from organizational, political, economic, social and other forces that shape them (FederalFacilitiesCouncil, 2001, Preiser and Vischer, 2005). POE is also considered as the final step in a cyclical process that closes the 'design loop' of a new or refurbished building. Without this process the individuality of each building is even more reinforced and seen as a single case, in which the complexion of spaces, systems and occupants' practices are less apparent, offering even less predictable outcomes (Zimmerman and Martin, 2001:169, Preiser and Schramm, 2005).

POE studies provide the platform for knowledge feedback to improve a building's current conditions and operation as well as to guide design and operational issues in future projects (Zimmerman and Martin, 2001, Meir et al., 2009). This type of building knowledge 'feedback' has been described by Bordass et al. (2006:11) as a process of:

...learning from what you are doing or from what you and others have done to understand where you are and to inform and improve what you are about to do.

The 'lessons learned' or 'feedback' refer to studies and research programmes which aim to collect, archive and report information about the level of success (or failure) of building processes, technologies and other building related areas. The subjective and objective feedback gained offer short, medium, and long term benefits (Preiser and Schramm, 2005:21, Meir et al., 2009:191) serving to improve the quality, performance and life cycle

efficiency of future buildings (FederalFacilitiesCouncil, 2001:1) and particularly to avoiding the repetition of mistakes. To a large extent (e.g. FederalFacilitiesCouncil, 2001, Zimmerman and Martin, 2001, Leaman et al., 2010, etc.), POE findings also allow us identify where users (occupants) behaviour undermines the intended functioning of the building systems and at what level users' knowledge and training can improve their operation, especially when complicated interrelations are not straightforwardly to analyse (Meir et al., 2009:209).

However, despite all the previously discussed benefits, POE studies also suffer from some serious limitations such as: high costs for the real estate industry; split incentives between actors where institutional and professional fragmentation of different authorities results in professional defensive reaction to the process; timeline constraints after project completion; a lack of researcher skills that range from cost-accounting evaluation to technical measurements of building performance and surveys of user (occupant) behaviour; and finally a lack of indicators and accompanying benchmarks as a result of these limitations in profession fragmentation and skills (Zimmerman and Martin, 2001, Vischer, 2001, Bordass and Leaman, 2005).

Therefore, the scale and scope of POE studies in buildings, both at national and international level, can range significantly. Two broader categories can be distinguished: those of lateral studies looking into a limited number of building aspects from a macro perspective (identifying relations between housing, neighbourhood and peoples' perceptions) in an extended number of cases; and those of in-depth studies focussing on detailed analysis in a single case study of all the complex interrelated aspects (evaluating occupants' satisfaction, comfort or the interaction with specific technology) (Meir et al., 2009:191-202, Topouzi, 2011). Consequently their different levels can be classified (Preiser, 2001:11) as follows:

- Indicative: often consisting of selected interviews and building walk-through, to give evidence and raise awareness of the most important failures (or potentials) in a building's performance;
- Investigative: giving a greater depth on building performance and functionality that offer systematic and detailed understanding of the source of problems affecting the overall building performance; and
- Diagnostic: creating new knowledge on complex aspects of building performance by linking physical measures with occupants' subjective responses on perception of measures and usage.

These levels can be summarized in four expedient types that contribute on: building-behaviour research or accumulating knowledge; feeding into pre-design programming; strategic space planning; and finally on the capital asset management (Vischer, 2001:25). As expected, each of these POE approaches often depends on the conflicting viewpoints of different stakeholders (i.e. building manager, building user, architects, engineers and technical consultant, clients, owners or other institutional stakeholders) (Meir et al., 2009). These POE approaches discussed here provide the approaches and tools adapted from this study and discussed in Chapter 4.

3.5.2 The UK's building performance evaluation context

In recent years, interest in building performance evaluation in the UK has grown significantly. A large part of the POE studies in the UK are funded by Government often using academically defensible research methods to study mostly public buildings. Especially for the Government's private financing initiative (PFI) projects, more weight is given to project's outputs than inputs provided by stakeholders (Preiser and Vischer, 2005). The PROBE (Post-occupancy Review of Buildings and their Engineering) approach is the most well-known POE methodology in the UK for larger buildings. This methodology is used to provide evaluation feedback on recently completed non-domestic

buildings in the light of their technical performance, energy performance and occupant satisfaction (Bordass et al., 2001). PROBE's quantitative tools dealing with the building's 'hard' (physical) issues use CIBSE's Energy Assessment and Reporting Methodology (EARM) and air pressure test methods, whilst for the 'soft' (behavioural) issues the Building Use Studies' (BUS) occupant questionnaire is used, both of those providing reference benchmarks (Leaman, 2003, Preiser and Vischer, 2005:75). At the same time, at the role of incubator, the Usable Buildings Trust (UBT) promotes the development of POE approaches and effectively provides important feedback resources on UK's non-domestic buildings' actual performance. Even though housing might share common aspects with non-domestic buildings in post-occupancy evaluation methods, Stevenson and Rijal (2010:551, Table1) show some of the fundamental differences between the two building sectors. Housing occupants are in the role of 'building manager' (Stevenson and Rijal, 2010) accounting for both building and household factors that affect overall building performance. To understand individual behaviour, the level of concern and decision, tenure expectations, needs, controls, functions and routines, requires new evaluation methods for housing that take into account these variables.

3.5.3 POE methods and techniques for domestic buildings

To date, for many researchers, the main concern is to establish a concrete methodology that links the technical assessment of physical performance with the analysis of human behaviour of occupants of the space. This suggests bridging the gap between building performance modelling – estimated performance – and reality in terms of the actual energy in use (Page et al., 2008, Mahdavi and Pröglhöf, 2009). Domestic buildings are complex systems and their interaction with occupants (users) adds considerably to this complexity. Their compound interrelations (creating complex STS) require robust post occupancy

evaluation methods with multilevel techniques and multifaceted triangulation systems to investigate the current energy gap (estimated and actual performance).

At its inception, POE draws on an extensive toolkit of quantitative and qualitative methods. On the basis of techniques and information these methods can provide, there are two rough categories: physical measurements, plan analysis, monitoring (indoor air quality and thermal performance) and energy survey on the one hand, and walk-throughs with on-site observations, questionnaires with (semi-structured or structured) interviews on occupant behaviour, usage, satisfaction and comfort on the other. Physical measurements, fabric testing, monitoring and energy audits provide the key quantitative parameters regarding building energy performance, such as (internal and external) temperature, relative humidity, air quality and CO₂ levels, light and noise levels and primary energy consumption. Building surveys, with plan analysis and walk-throughs, are used to capture both quantitative and qualitative information on the building or building system and measures. They reveal problems and capture details on actual energy use and use of space. In diagnostic or in-depth level approaches there are cases (e.g. Stevenson, 2004) in which occupants are encouraged during the walk-through process to indicate use or technical issues of their concern. Through this process behavioural aspects can be observed and features, e.g. maloperation or customizations, affecting the intended design and performance can be noted.

Depending on the level of approach in the POE process, the 'negotiation with the user' (Watson, 2003) through questionnaires can vary from a structured questionnaire survey (e.g. BUS occupant survey for houses) to in-depth semi-structured interviews (e.g. Stevenson, 2004, Gupta and Chandiwala, 2010); nonetheless, all cases aim to establish absolute objective data (Leaman and Bordass, 1999). Questionnaires collect quantitative information on occupants' perceptions of environmental comfort, personal control,

background information, health, design, satisfaction and needs (Cohen et al., 1999). For instance, BUS collects information from occupants on these aspects for 49 variables falling into twelve major groups (Leaman and Bordass, 1999). The numerical nature of this type of interviewing technique and its scoring system can enable statistical analysis of occupants' perceptions against benchmarks (Levermore, 1994). Semi-structured interview techniques provide in-depth qualitative data on the same aspects (thermal comfort, satisfaction and controls) allowing occupants' discussion beyond specific questions in an open-ended way and on their own terms. This can bring forth an occupant's views, level of tacit knowledge and own value-system that possibly affects, their perceptions of building performance and design; it can also draw out insights on behavioural aspects relationships and interrelationships that help in better understanding the occupant's interaction with building controls and use.

Additionally, in collecting feedback from tenants, recent POE research attempts (Gupta and Chandiwala, 2010) to bring forward a range of techniques in diaries and interviews stemming from social science research. In this study's approach, techniques as such questionnaires, open-ended semi-structured interviews and structured diaries or logging sheets are administrated either in the short term (one-off feedback) or the long term (periodically repeated). Interviewing and walkthroughs using such techniques for in-depth feedback collection, even though they are considerably more time consuming as evaluation methods compared with a typical BUS questionnaire, allow a higher level of information detail. Using combined methods approaches, is possible to generate feedback on occupants' actual use of the building at a level of detail that cannot be provided by simple survey methods.

However, in the synoptic overview of published recent POE studies by (Meir et al., 2009:192-211), residential building POEs vary significantly in terms of scope, evaluated

aspects and in particular methodologies used. The scope of these studies covers building type, construction and (or) technical measures; the evaluated aspects mainly rely on either indoor environmental audits with basic user satisfaction surveys, or (and) energy audits occasionally carried out as physical monitoring exercises. Often, in residential POE studies, quantitative and qualitative methods, from different disciplines, are not related to each other or can vary significantly in the level of detail that they elicit. With building performance techniques for residential buildings remaining relatively undeveloped compared to other sectors, an increased canonization of POE techniques is required.

a. Current post occupancy evaluation studies

As mentioned previously, although in the UK there are several BPE studies using POE techniques for non-domestic buildings, the residential sector is still quite undeveloped. In the UK, recent studies focus either on a large number of units evaluating specific issues or multiple issues in small case studies (Stevenson and Rijal, 2010:551). Current research (Gupta and Chandiwala, 2010, Stevenson and Rijal, 2010) employs BPE methodologies in both new and refurbished zero- and low-carbon houses. These studies report vast differences between the actual measurements and model estimates, revealing how poor modelling tools are when checked against real occupant behaviour and energy use. Given that there is very little in housing evaluations currently in the UK, compared to other sectors, this section will provide an overview of those studies that include both quantitative and qualitative methods, bringing forth holistic POE approaches.

The study of Stevenson and Rijal (2010) develops a methodological strategy for evaluation of a new house ‘zero-carbon’ prototype taking into account critical quantitative and qualitative factors. In the quantitative factors, energy use is assessed by SAP2005 and includes physical measurements. The study investigates in-depth qualitative factors inherent within the specific prototype house design examining aspects of ‘interactive

adaptivity' (Cole et al., 2008). It introduces a combination of standard interviewing methods and innovative POE methodological approaches to investigate a wider than usual range of observations on interrelated factors on user's behaviour and windows and doors, as well as occupants' perception regarding comfort and control. The study uses triangulation of the monitored energy with loggers, interviews and walkthroughs for the same period and reveals uncontrollable aspects related to occupants' understanding of control. This suggests triangulation of different methods as a mean to overcome the particular limitations of individual methodological approaches, which in many instances can help to explain the complex interaction of factors involved when user behaviour is related to building performance.

Another example is Gupta and Chandiwala (2010) who in their recent empirical study develop a systematic pre- and post-refurbishment BPE methodology, extending existing post occupancy evaluation methods and techniques for physical measurements and occupant feedback with new variants, focussing on occupants' perception of their comfort, satisfaction, behaviour, electric appliance usage and refurbishment expectations.

Summary and discussion

From engineering and economics to social psychology, research on household energy use is scattered across different disciplines, theoretical and methodological approaches. This has been the major constraint narrowing understanding of energy consumption of the building system, as influences on energy use are seen as individual factors and not as co-determinants in a building system as a whole. Technical approaches focusing on the building performance problem, from merely physics and engineering perspectives, consider 'default' average users and not a building system controlled and occupied by real persons. Energy use determinants and interrelations explored by such approaches vary based merely on buildings' characteristics. Non-technical approaches may offer a

theoretical foundation that interprets human dimensions in a building's energy use, but again merely from demographic, behavioural and socio-economic perspectives. From numerous theories in social sciences to explain buildings' energy behaviour, the review discusses the main sociological theories, cultural and practice theories and their different approaches and key elements in understanding/interpreting practices in household energy. From the prominent dualism between technical and non-technical approaches, the discussion that follows explains the combined interdisciplinary socio-technical whole-house approaches as these are reviewed in recent studies in the energy efficiency field. Mainstream approaches to investigate correlated direct and indirect (e.g. Aune, 2007, Carlsson-Kanyama and Lindén, 2007, Steemers and Yun, 2009) technical and non-technical factors, like science and technology studies (STS), user-centred theory approach, interactive adaptivity and adaptive thermal comfort are reviewed. The occupant's interaction with the building system and other 'whole house' refurbishment considerations set the study's area of exploration in the context of the current literature. Current empirical socio-technical studies in houses energy use discussed on view of the current building performance evaluation approaches, methods and the techniques that are employed to capture technical and non-technical aspects. In this chapter, the context of established theories, approaches and methods reviewed sheds light on the current constraints in single discipline and simplified explorations of building energy use. This justifies the background of elements that this study borrows from such approaches to develop its socio-technical approach presented in the following chapter.

Chapter 4: Proposed approach

The literature review explored the social housing context and policy background along with energy use approaches as these have been modelled, designed and implemented in the UK's housing stock. Technical, non-technical and socio-technical issues in domestic energy use were discussed in Chapter 3 to highlight the different discourses among disciplinary approaches, as well as the variation in methods that each of those uses. The purpose of this chapter is to discuss the rationale of using a socio-technical approach for the research design of this empirical study. This chapter provides an outline of the synergies and links between approaches involved in household energy use studies; in addition it presents the conceptual framework that the study has developed by integrating different methodological and theoretical approaches that allow physical and social factors affecting energy use to be examined holistically; and adds to the existing studies that combine social and technical approaches to energy use, with a specific focus on innovation. The chapter discusses the data sources used, providing the background on the RfF dataset; and provides an account of the design and data collection process.

4.1 Rationale for an interdisciplinary socio-technical approach

A household's energy use is a complex system involving individuals (occupants) interacting with technical measures/interventions. In such a system of interrelated and interdependent behavioural and technical components, interaction is difficult to examine when simplified or single approaches (technical or social) are used. The literature on empirical studies is replete with examples of approaches that, despite their merits and limitations, all emphasise socio-technical factors and dependencies (e.g. Hitchcock, 1995). It is widely acknowledged that domestic energy use requires knowledge and techniques from several disciplines (i.e. engineering, physics, social science, building studies, and economics); however, studies' approaches still lack combined methodological and

theoretical canonization. Even if, in several studies of energy use, behavioural and technical variables and their dependencies can be captured and described clearly, major constraints appear in the methods of collecting and analysing socio-technical factors. This is especially the case when methodological shortcomings in data collection significantly constrain data quality and type (qualitative or quantitative), thus limiting the selection of a theoretical framework and techniques for analysing socio-technical factors.

In empirical studies combined (mixed) approaches can underline the links between a household's system components, to allow household energy use to be investigated holistically. This requires high resolution of both qualitative and quantitative data inputs, as well as the equivalent emphasis on the methodological and theoretical approaches applied in the collection and analysis. The reason for this is to limit the risk of creating socio-technical links that, instead of using techniques and combined methods, result in disparate methodological and theoretical combinations described by vague frameworks. As a consequence, such approaches can narrow data collection and analysis significantly generating outcomes that limit comparisons with other studies' findings.

Clearly, energy consumption numbers by themselves, either expressed as in energy units or as energy cost, cannot alone explain energy use or occupant interaction with low-carbon interventions in refurbished houses. Observations and householders' behavioural narratives are needed to tell the 'story' of a household's energy use, but a user's interaction is certainly not just a matter of storytelling. Energy research examining such complex interventions, with interrelated technical and behavioural aspects, cannot be reduced either solely to numbers and empirical data or to single techniques and theoretical frameworks, but rather needs to involve a dynamic interdisciplinary process that links together problems, theories and methods. An interdisciplinary strategy was developed in this thesis to overcome limitations related to the complex and disciplinarily subjective nature of

socio-technical factors in occupant interaction with low-carbon technical changes. In an attempt to gain research depth, the study’s approach creates interdisciplinary synergies and links between the different methodological and theoretical approaches, to examine household energy use holistically. An outline of the study’s interdisciplinary socio-technical approach is illustrated below (Figure 30).

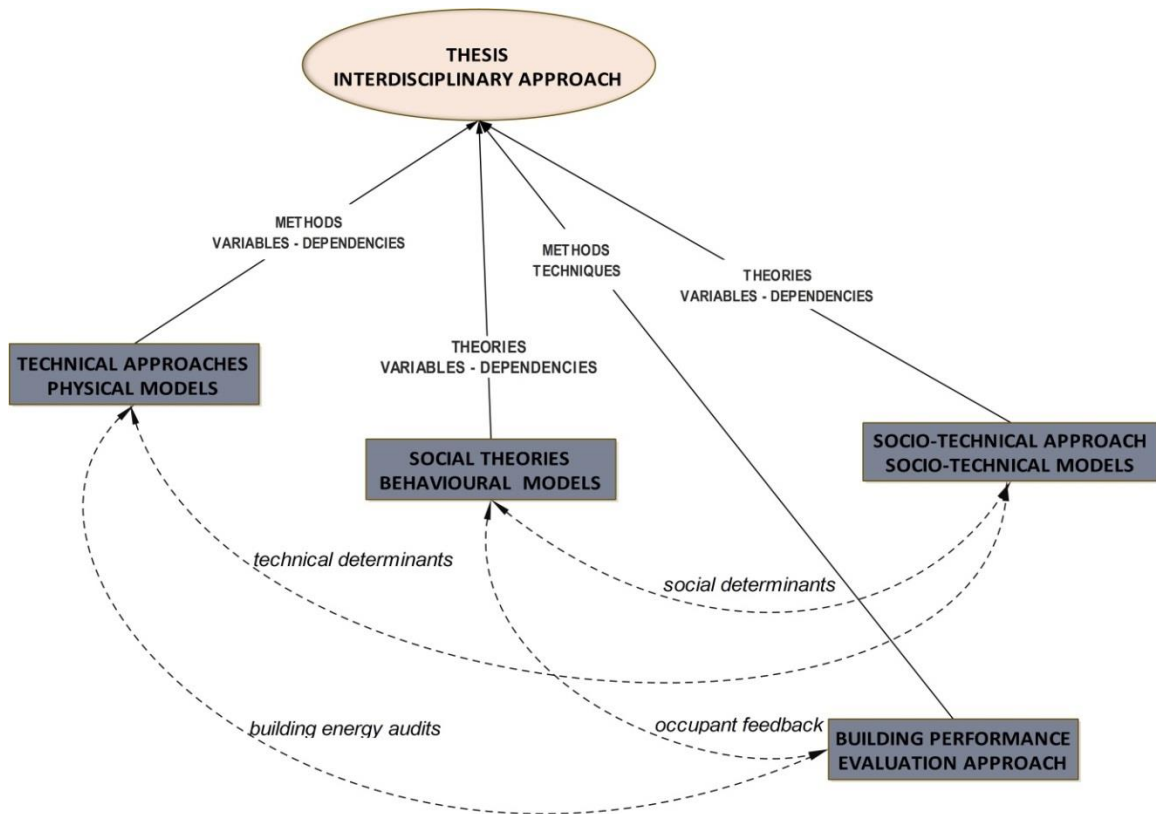


Figure 30: The study’s interdisciplinary socio-technical approach and links between different established approaches.

Technical approaches offer methods to investigate direct and indirect variables (e.g. heating controls, natural and mechanical ventilation controls), physical parameters (e.g. weather conditions), determinants (e.g. building’s context, fabric, systems) and dependencies of buildings related to the fuel source type and climate. Calculation methods from physics models were used by all applicants¹⁵ in the RfF competition to estimate the

¹⁵ As explained in the Key definitions section the term ‘applicants’ is referred to the RfF competition programme participants; and were those to provide the TSB and EST evaluation process with the monitoring data, cases documentation and technical building tests.

heat balances in households' energy use, allowing comparison between the 'as designed/modelled' and in-use stage in the 26 RfF cases, i.e. the predicted and actual energy performance. Physical variables and dependencies in households' energy use identified in previous studies from engineering, architecture and building physics approaches provided the context for current knowledge claims (theories) and the linkage between theories and this thesis investigation.

In the study's interdisciplinary socio-technical approach, social science theories offered the theoretical background used for the analysis of non-technical variables in household energy use. Socio-demographic and behavioural variables and dependencies from previous studies provided the broad themes and explanations of energy use practices. The integration of the two disciplinary research traditions in socio-technical approaches enabled investigating the household system as a whole. Previous socio-technical studies in households provided the methods and techniques for variable aggregation (or disaggregation) related to energy use. Existing methods of building performance evaluation were employed for the data collection and the techniques extended to meet the study's research requirements. These theoretical socio-technical perspectives were used to explore the actual use or interaction by examining households 'as occupied', by using the socio-technical methods of existing empirical studies to analyse interactive relations between occupants and building elements.

The study's approach was structured in such a way that the methods and techniques were able to answer specific research questions. The aim of this was to capture explicit aspects of 'user' interaction with a range of specific technological innovations and passive design measures in small sample of social housing. The same methodological and theoretical approaches were used in all stages of data collection and analysis. They focussed on investigating, observing and analysing specific aspects of control-oriented user behaviour

related to low-carbon buildings' environmental systems, to avoid generalisations. The techniques used for data collection (recorded, observed and reported data) provided high resolution data for each household to support socio-technical analysis. This approach also sheds light on mixed methodological approaches that might be used in larger samples and/or with different housing types, allowing us to move towards an integrated understanding of the user experience in low-carbon building environments. The design of these links between methodologies and theories implemented in this study is discussed comprehensively in the study's conceptual framework in the following sections.

4.2 Conceptual framework

The study developed a conceptual framework as an intermediate theory to connect all aspects of the study's inquiry, involving the problem and purpose definition, literature review, methodology, data collection and analysis. The purpose of this conceptual framework is to map the courses of action, giving the different approaches coherence with respect to the empirical inquiry. The combination of theories comprises the theoretical foundation of the study required for data analysis and interpretation of socio-technical variables. It also allows the investigation and interpretation of complex interrelations between those variables that elucidates physical and behavioural determinants by using classification parameters.

The conceptual framework (Figure 31) incorporates elements borrowed from existing established social theories, technical and socio-technical research and established methodological approaches. For example, from Steemers and Yun (2009:636, Figure3) diagram, the links between factors affecting domestic energy use (Appendix 4) have been adapted to the study's conceptual framework. In the study's approach to refurbishment interventions and occupants, a system of practices is structured in which agents,

interactions and individual user behaviours are combined to determine a building's overall performance.

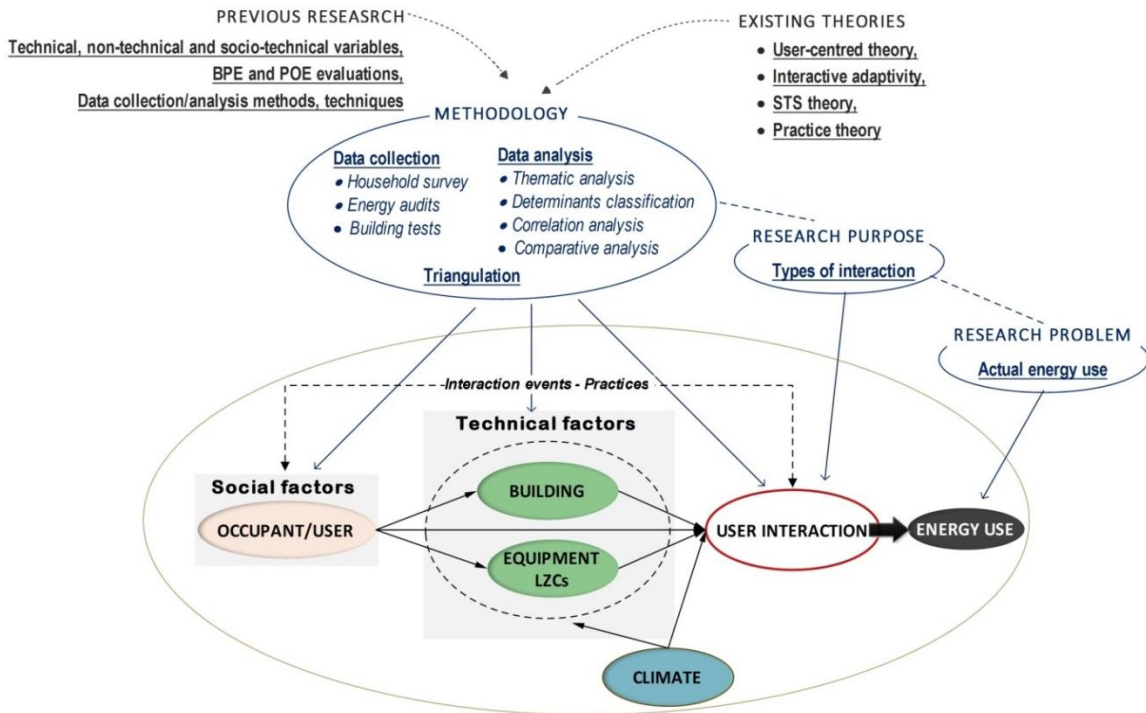


Figure 31: Links between components in the study's conceptual framework.

The notion of ‘interaction’, as discussed in previous chapter (section 3.4.1), is used in the study to describe control-oriented actions between occupants’ behaviours and elements of the building system and the environment. Aggregated, these interactions influence occupants’ wellbeing, health and comfort and determine occupants’ interaction with their environment (Bluyssen, 2009). Perspectives of single theoretical frameworks can be useful to examine specific aspects of a household’s energy consumption. However, the complexity of user interaction and the interrelation of factors require a combination of more than one theory (Figure 32).

The main principles of the ‘user-centred’ theory were used to link the information generated by the systematic empirical BPE methods. User-centred theory as applied in this study accepts that the building environment exists to support the activities of its occupants;

therefore, variables related to the user(s) and their activities were thoroughly examined. According to this theory, the occupant (user) experience is determined by how occupants are affected and respond to that environment. In this respect, the interaction with the low-carbon improvements were examined through the lens of the users' experience of the building's refurbishment interventions. Another contribution of this theory in was in understanding how space within the household (personal, semi-private, social/common, etc.) is defined, along with the ways the building environment is related to occupant practices and occupancy patterns.

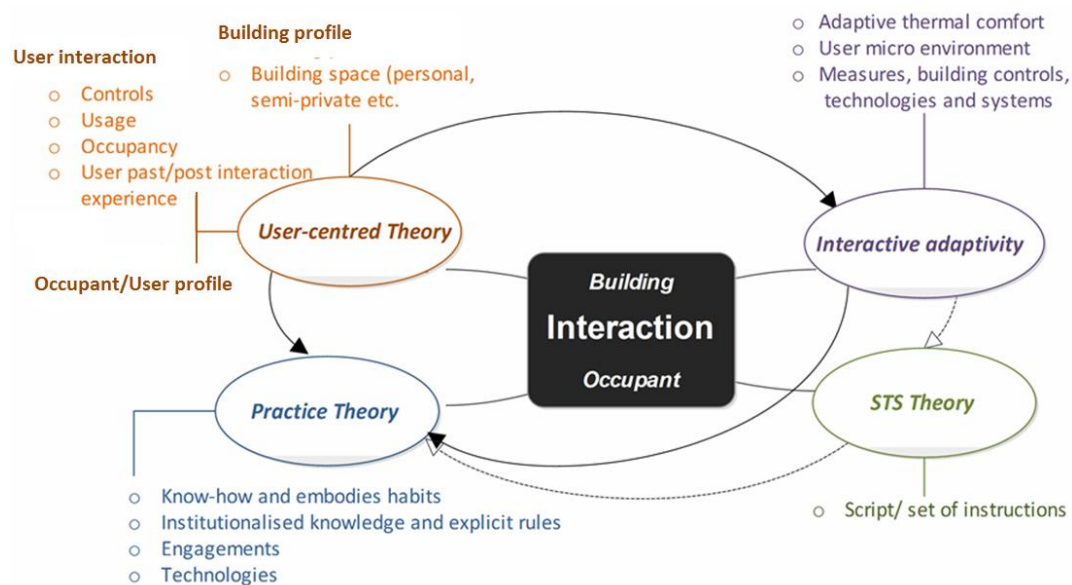


Figure 32: Links between theories and their components as used in the study.

‘Interactive adaptivity’ was used to draw attention to particular interactions. Using the broader definition of ‘adaptation’, the conceptual framework uses the assumption that occupants are not passive recipients of the environment -especially when changes occur- but interact with it using different ways to achieve conditions of comfort. In this respect, the occupant (user) operates the building environment by interacting with building controls, technologies and systems to create their own microenvironment. As discussed in Chapter 3, the study uses three distinct modes of ‘adaptation’ from the literature (e.g.

Brager and de Dear, 1998, Nicol and Humphreys, 2002, Liu et al., 2012a): physiological, psychological and behavioural adaptation. The effects of these three categories of adaptations were evaluated in terms of perceived level of environmental comfort, control and their past-experiences of both. This enables an understanding of the dynamic processes involved in occupants' interactive adaptivity, which is influenced by multiple factors such as health, individual characteristics, climate, culture, economics, habits, expectations, thermal comfort preferences, etc.

The interactive adaptivity approach moves a step forward from previous user-centred considerations by focussing on particular actions that occupants carry out to create their new (post-refurbishment) microenvironment. In this respect Science, Technology Studies approaches were utilised to illuminate questions (e.g. Research Questions 1, section 1.3) related to the type and extent interaction is 'scripted' by the low-carbon measures. The study is focussed on what is 'pre-scribed' (or prefigured) by the technical intervention and what level of interaction is left to the users (occupants) to create their own microenvironment. It also accepts the approach of Schatzki (2002) that prefiguring can make actions either easier or harder, shorter or longer, and acceptable or not, when these are compared with other actions. The study also borrowed elements from practice theory (such as know-how and embodied habits, institutionalised knowledge and explicit rules, engagements and technologies), as used and defined in the empirical study of Gram-Hanssen (2009) on households' energy consumption. These elements helped to identify occupant routines and technological structures that contribute to a household's energy-consumption practices. Practice theory also helped to organise pieces of data that seemed unconnected to one another or not directly relevant to the study's main research questions. It achieved this by shedding light, for instance, on relationships between different sources

of occupant knowledge and control-related behavioural trends, which hold everyday practices together.

The study relied on previous research for selection of technical, social and socio-technical variables and determinants involved in household energy use (see Appendix 7, Table 21). Findings from previous studies (e.g. Mahdavi and Pröglhöf, 2009), suggesting that occupant (user) interactions are difficult to identify and predict at the level of a single person, were taken into account to structure the empirical inquiry. In this respect, this study uses long-term observational data from households, to provide households' interaction patterns established by control-related behavioural trends, patterns and relationships for groups of occupants and building services.

Methodological approaches and tools from building performance evaluation and post-occupancy evaluation studies were used to evaluate the gap between actual energy performance (in-use) and what was predicted ('as designed' and 'as modelled'). A selection of quantitative and qualitative approaches for data collection from previous POE studies on households structured the study's toolkit of methods. BPE and POE methodologies use the term 'occupant perception' to describe the occupant's/user's perception of comfort with regard to the factors determining a building's indoor environmental conditions. This study focuses on occupant/user interaction and uses Gibson (1986) term 'perception-in-action' as user 'perception' often describes static conditions and not use. Previous POE studies (e.g. Stevenson and Leaman, 2010) have shown that triangulation of data and methods can make a significant contribution to explaining the complex interactions involved in user behaviour, systems and overall building performance. The triangulation applied in this study enabled correlation of occupants' 'doings and sayings' by linking quantitative energy data with the users' practices, as identified and analysed by practice theory approaches. Correlation and regression analysis

were applied to describe the relations and dependencies between space heating, ventilation, and domestic hot water. These approaches, which were used in previous studies (e.g. Steemers and Yun, 2009), enabled determination of the interrelationships of space heating and ventilation variables and the extent to which these affect overall household energy use.

4.3 Research design

Taking into account the interdisciplinary approach of the study, a mixed-method research design was developed to link the conceptual framework, research objectives, type of data, and methodological approaches to collection, analysis, and interpretation.

Mixed-method approaches are increasingly popular in empirical energy studies. Particularly in building performance evaluation studies, such methods (e.g. Gupta and Chandiwala, 2010, Leaman et al., 2010) have provided valuable insights into energy use related to technical and behavioural interventions. There is a wide range of classifications (typologies) of mixed-method designs in the literature, each drawing on different disciplines and using different terminologies. The central premise of mixed-method research is that combined qualitative and quantitative approaches can provide more comprehensive evidence and a better understanding of the research problem than either approach alone (Creswell and Plan Clark, 2007). Although mixed-method typologies can be valuable for making broad research decisions, they can also limit diversity by leaving out important components of the design (e.g. conceptual framework, data validity strategies like triangulation, etc.), or make unclear interrelationships between qualitative and quantitative parts of a design. Traditional mixed-method design typologies tend to emphasise linear research approaches in terms of their conception of design, in which design components are seen as phases or stages rather than interacting components of a complex whole (Maxwell and Loomis, 2003).

Given the complex nature of the socio-technical factors embedded in the research questions, the mixed methods components employed were viewed as a whole system rather than a sum of individual parts and procedures. Thus, the interactive design approach of Maxwell and Loomis (2003) was applied and adapted to respond to the thesis requirements. This research design approach represents ‘design-in-use’ decisions that highlight the relationships between components. It has five components (Figure 33): the study’s purposes and goals, conceptual framework, research questions, methods and validity.

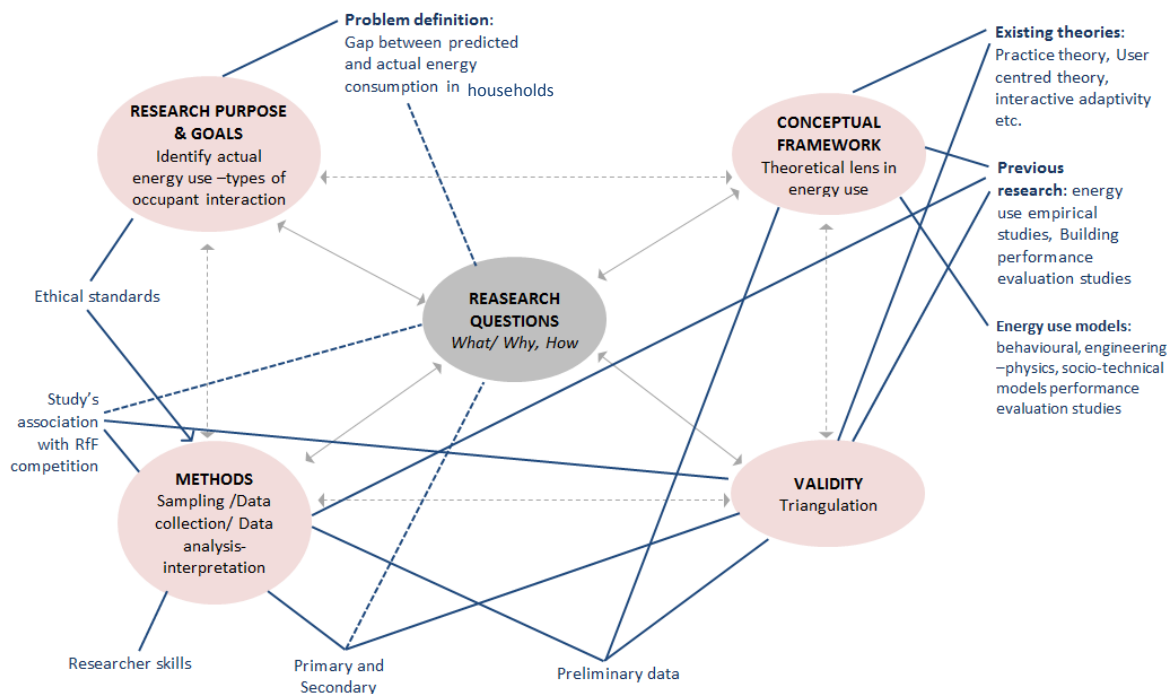


Figure 33: The study’s mixed-method research design (adapted from Maxwell and Loomis 2003:247, Figure 9.2).

Using approaches from social science, behavioural research and technical evaluations, the study mixes quantitative and qualitative approaches at all stages of the investigation to understand complex aspects of the energy use problem. The purpose of the three key areas distilled from the main research questions about the central phenomenon of interaction is to expose ‘how’ and ‘why’:

- Occupants relate to household energy use, in terms of socio-demographic factors and behavioural determinants;
- Technical retrofitting interventions and low-carbon measures relate to household energy consumption; and
- Occupants' interaction with the technical low-carbon interventions affects household energy use.

For each of the three key areas, the occupant (user), technical aspects (building fabric/systems), and interaction (energy use/ operation), quantitative and qualitative approaches are mixed. Using a combination of techniques (e.g. data cross checking) significantly limits data divergences and practical constraints (e.g. interviews coordination) in data collection (Figure 34).

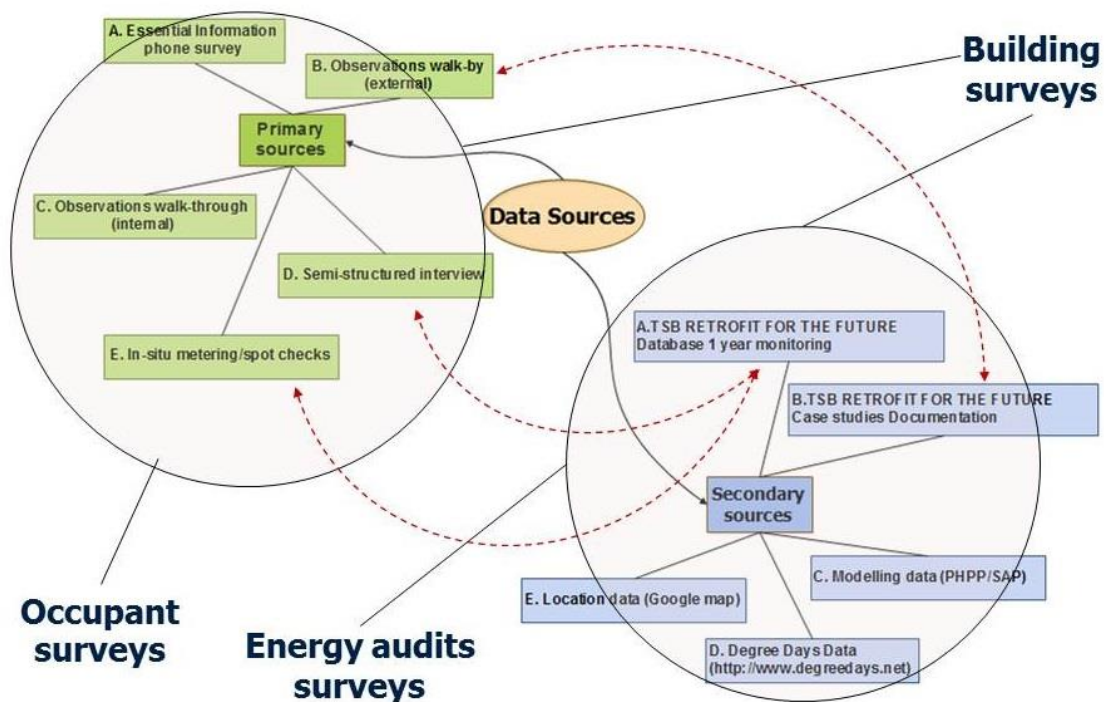


Figure 34: Outline of the study's techniques in data collection.

The costs in qualitative methods (e.g. related in-depth interviews), was reduced by the study's association with Technology Strategy Board RfF competition procedures; the quality of data was advanced by combining interview skills and background knowledge of

the topic. Drawing on different methodological and theoretical approaches, the two types of data were integrated and analysed, strengthening validity through triangulation. The selected qualitative and quantitative methods allowed this study to:

- Better understand the energy use (interaction) problem by triangulating quantitative and qualitative data from both physical (technical variables) and behavioural (non-technical/social variables) determinants;
- Explore occupants' views and define interactions numerically in relation to passive, low-carbon measures and building services; and
- Effectively disseminate findings of occupant interaction with low-carbon measures to different disciplines and sectors.

4.3.1 Qualitative, quantitative and triangulation methods as complements

The advantage of qualitative methods is the depth of data they provide, which is required to analyse complex socio-technical factors related to user control energy behaviour. As Crosbie (2006) discusses, the drawback to these methods can often be their reliability, given that they are susceptible to self-reporting bias. The sample size and type of data does not allow statistical analysis or generalisations of findings. However, from the Twin River's project in the early 1970s (Socolow, 1977) to date, progress has been made to overcome reporting biases. Therefore there is a large number of household energy consumption studies, (e.g. Harrje and Grot, 1978, Hunt and Gidman, 1982, Gupta and Chandiwala, 2010, Stevenson and Rijal, 2010, etc.) in which limitations of self-reported energy consumption are addressed by collecting data on households' actual energy consumption.

In the interactive mixed-method design proposed, there are links between qualitative (QUAL) and quantitative (QUANT) approaches at all stages. The way each approach has contributed to the study's design is summarised in Table 4.

Throughout the process the formulation of the QUANT oriented question on 'how much' and 'why' interaction affects energy use is informed by the QUAL oriented 'how' question and vice versa. Although the 'why' can also be found in several qualitative studies, it implies a quantitative orientation of cause and effect, an explanation of something occurred. According to Creswell and Plan Clark (2007) such an explanation diverges from the nature of qualitative research, which looks for an in-depth understanding ('why') of the central phenomenon, not for sole explanations.

<i>Interactive mixed-method design</i>			
	<i>Qualitative</i>	<i>Mixed methods</i>	<i>Quantitative</i>
Research questions	<i>QUAL.</i> (What type and how 'interaction' occurs)	<i>QUAL. and QUANT. combined</i>	<i>QUANT.</i> (Why does the 'interaction' occurs)
Role of research	<i>Exploratory (Means to explore interaction actors (occupants/users) and physical components (technical/measures)</i>	<i>Merge both</i>	<i>Confirmatory, (means to triangulate findings)</i>
Relationship between researcher and subject	<i>Close</i>	<i>Both</i>	<i>Varies (both close and distant)</i>
Researcher's stance in relation to data collection	<i>Direct</i>	<i>Both</i>	<i>Both direct and indirect</i>
Relationship between theory and research	<i>Emergent</i>	<i>Both</i>	<i>Confirmation</i>
Research strategy	<i>Semi-structured</i>	<i>Combined</i>	<i>Structured</i>
Research timing	<i>1 year</i>	<i>Concurrent</i>	<i>1 year</i>
Nature of data	<i>Narrative, visual ('soft data')</i>	<i>Soft and hard data combined</i>	<i>Numeric ('hard data')</i>
Scope of findings		<i>Social and technical combined</i>	

Table 4: Outline of the role of mixed qualitative and quantitative methods in the research study.

The qualitative approach addresses the ‘how’ by focussing on processes of using the low-carbon measures while the quantitative ‘why’ approach quantifies to some extent the energy use outcome. The qualitative and quantitative data on technical and behavioural variables were collected concurrently within a year and merged to provide comprehensive analysis of occupant interaction. Households’ energy usage, is affected by technical dependencies and occupant behaviour (independent variable).

The quantitative data consisted of physical and behavioural determinants (Table 5), was collected using techniques such as building and energy audits and an occupant survey. Specifically, the physical monitoring (quantitative instruments) is used to measure the relationship between an occupant’s energy usage practices (occupant’s behaviour/ user interaction, building performance) and overall household energy consumption (dependent variable). At the same time qualitative data on behavioural aspects related to usage (interaction) and systems controls are explored, by using in-depth semi-structured interviews with the householders and of low-carbon retrofitted properties.

	Physical determinants	Behavioural determinants
Quantitative	Building audits <ul style="list-style-type: none"> ▪ Building context (e.g. building type, age, type, size, etc.) ▪ Building fabric (e.g. insulation, windows, extensions, etc.) ▪ Building systems (e.g. CHP boiler, heat pumps, PVs, MVHR etc.) ▪ Building tests (e.g. airtightness, thermal imaging, etc.) 	Occupant survey <ul style="list-style-type: none"> ▪ Demographic (e.g. age, number of occupants, gender, etc.) ▪ Economic (e.g. income, bills payment etc.) ▪ Occupancy patterns (e.g. typical week occupancy etc.) ▪ Environmental comfort (e.g. indoor temperature conditions, natural light, design etc.)
	Energy audit <ul style="list-style-type: none"> ▪ Energy consumption (e.g. gas, electricity) ▪ Energy generation (e.g. electricity) 	<ul style="list-style-type: none"> ▪ Systems controls (e.g. heating system thermostat, TRVs, MVHR booster, Wattbox etc.)
Qualitative	Building survey <ul style="list-style-type: none"> ▪ Energy usage (e.g. environmental comfort, design, etc.) ▪ Personal systems control (e.g. measures/ systems demonstration usage etc.) 	Occupant in-depth interview <ul style="list-style-type: none"> ▪ Energy behaviour (e.g. past/post-experience, engagement etc.) ▪ Awareness, views, expectations (e.g. perception, values, lifestyle etc.) ▪ Satisfaction (e.g. comfort, health conditions, building's environmental state, controls, refurbishment process etc.)

Table 5: Quantitative and qualitative physical and behavioural determinants.

Previous studies (e.g. Stevenson and Rijal, 2010, Gupta and Chandiwala, 2010) on household energy use have ensured consistency and accuracy of findings by employing triangulation design procedures. To overcome limitations from self-reporting bias, the study's interactive design also includes smaller forms of data (both QUAL and QUANT) embedded within the larger data collection procedures. This allowed socio-technical variables to be investigated by cross-checking them against occupants' actions and statements (e.g. heating systems operation, comfort perceptions and on-site temperature

measurements). The methodological triangulation of independent sources (as illustrated in Figure 34, p.138 and Appendix 8) of data collected from combining different methods in the study (e.g. phone survey information, observations walk-by, walk-through and RfF case documentation) has contributed to consistently and accurately identifying socio-technical key issues in the sample and broadening their interpretation.

The links between qualitative and quantitative data in the study's research design are illustrated in Figure 35. The sample that the study's interdisciplinary approach applied is discussed in the following section, providing an understanding of the aspects considered in the study's research inquiry.

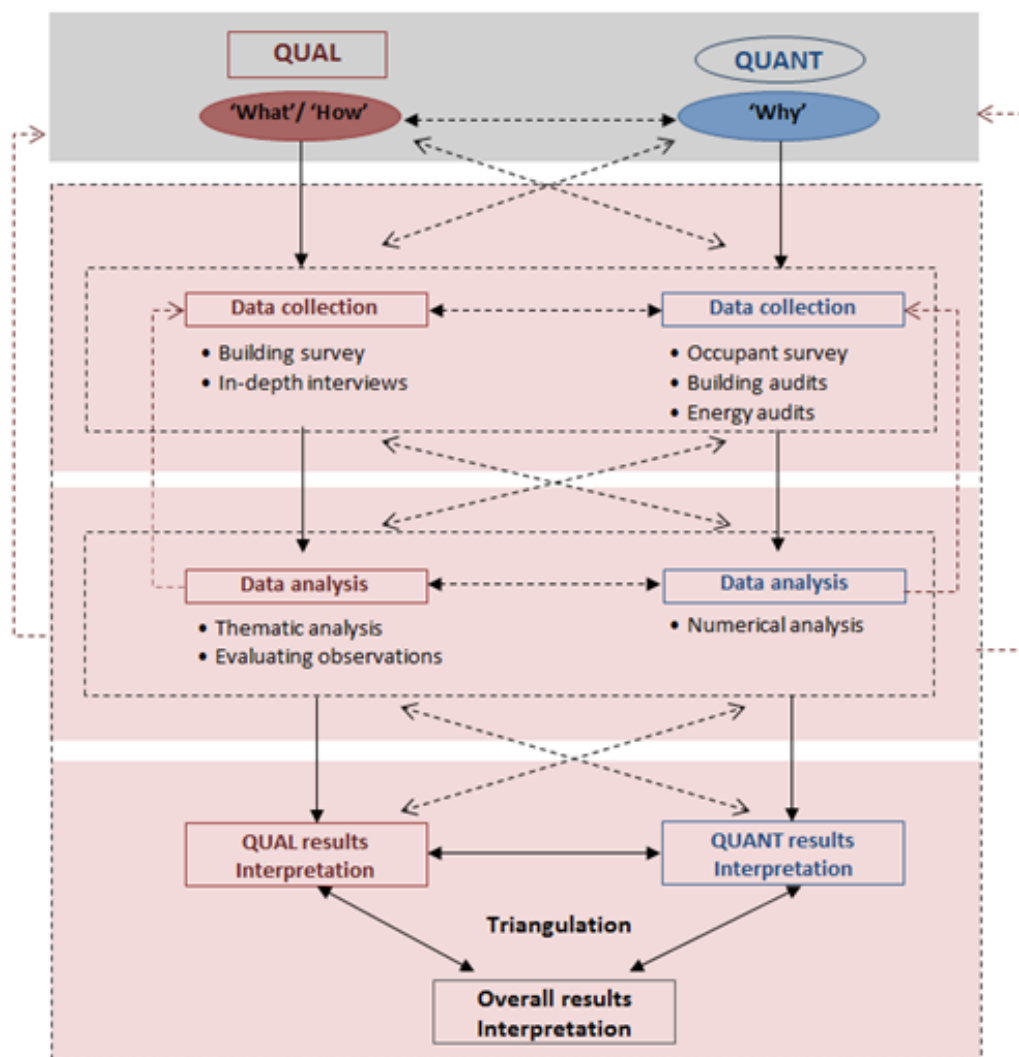


Figure 35: Qualitative and quantitative data in the study's research design.

4.4 Retrofit for the Future dataset

This study aimed to overcome previous studies' constraints in collection of empirical data, as well as other practical constraints of homogeneity, availability, time, cost and size of the data sample. This played an important role in selecting the study's dataset. The selected sample consists of 26 low-rise social housing units in the South East of England involved in the Retrofit for the Future (RfF) competition programme organised by the Technology Strategy Board (TSB, now known as Innovate UK).

The RfF dataset is currently the only large sample (n=119) of low-carbon deep refurbishments in the UK. The empirical material was selected to support the study's framework, research questions and objectives and ensure largely homogeneity in building characteristics and level of refurbishment interventions. Important aspects at the homogeneity level are the building type (low rise housing) and the social housing tenants. The monitoring strategy for quantitative data intended to acquire the same level of detail for all houses. The pre-refurbishment ('as designed/ modelled') and post-refurbishment ('as built') information for all the RfF refurbished properties was provided by TSB. Figure 36 below, outlines some of the main aspects that RfF data provides, which are considered to be most important for the study's conceptual and methodological framework.

KEY POINTS	CHARACTERISTICS	
a. Low rise housing types	Semi-detached (39%), Mid-terrace (38%), End-terrace (22%), Detached & others (1%)	
a. Rented social housing	Ownership status, type of tenants	
a. Specified reduction goals and targets (primary energy and CO ₂ emissions) for buildings energy performance	Similar or identical building environments, different occupants' energy usage practices	<div style="border: 1px solid black; padding: 5px;"> <p style="text-align: center;">STRENGTHS</p> <ul style="list-style-type: none"> ▪ Empirical data (quantitative and qualitative) ▪ Enables and advances comparisons ▪ Data accuracy ▪ Detailed data for each case ▪ No ownership property investment interests </div>
b. Specified protocol for the physical and technical refurbishment interventions		
a. Specified systems for data acquisition on monitoring process and energy audits	Similar monitoring systems (E.g. data loggers, sensors, etc.)	
a. Preliminary pre and detailed post refurbishment data acquisition	Number of cases with energy audits for both stages	
a. Estimated energy performance with specified modelling methods and tools	Refurbishment interventions for best practice evaluated under the same processes (e.g. SAP, PHPP)	

Figure 36: Key aspects of the study's data sample.

4.4.1 Dataset background

The RfF competition launched in 2009 was organised by TSB as a government funded schemes, supply the UK's 80% carbon dioxide (CO₂) reduction target by 2050. £17 million was budgeted enable the building sector to demonstrate refurbishment and retrofitting innovation in poor-performing social housing. The competition involved the refurbishment of 119 low-rise social housing units in total, across the UK. Through the competition, grants of up to £150k have been awarded to 87 successful project applicants (architects, building companies and other organisations as well as housing associations) that complied with the criteria of using innovative solutions and multiple system approaches, to achieve very high standards of energy efficiency and make deep cuts in carbon emissions. The 'whole house' approach was utilised in all projects. The low-carbon interventions were determined by technical specifications, performance baselines and CO₂ and primary energy targets provided by the Technology Strategy Board, as discussed in the following section. The whole-house approach requires a systematic handover process,

providing to the occupants information on the intervention and the low-carbon measures, systems and controls installed in their properties. This process is broadly specified leaving to project applicants' choice the time and type of training/demonstration to the occupants and the choice of key person to provide this.

One of the objectives of the RfF competition was to provide valuable insights into the 'as built' performance evaluation of such interventions, and also to feed into the overall evaluation of retrofitting processes, helping to shape efficient delivery of future schemes. To ensure these objectives were met, an extensive monitoring process was planned for two years, collecting both quantitative and qualitative data.

4.4.2 Outline of data sample characteristics

The majority of the social housing units in the RfF sample are managed by non-profit housing associations, with less than a half by local authorities. In all cases the social tenants meet allocation eligibility requirements before moving into the refurbished properties. An overview of the socio-demographic characteristics of the 26 selected properties studied is discussed in detail in the following sections.

The 119 refurbished properties spread all over the UK are all low-rise houses, of which 39% are semi-detached, 38% mid-terraces, and 22% end-terraces. Only 1% is detached and bungalows. Due to the diversity of building types and environments and in order for each of them to be in line with achieving the energy and CO₂ targets, flexible guidelines of technical requirements and specifications for all projects were provided by TSB (EST, 2009). Space heating energy was not included in the targets, but expected to be below 40kWh/m².yr (Ruysssevelt, 2011). Applicants were encouraged to calculate the proposed refurbishment interventions using the Standard Assessment Procedure (SAP) as the assessment method and/or a Passive House Planning Package (PHPP) for a performance

simulation (TSB, 2009). The targets were based on a CO₂ reduction of 80% and calculated with SAP 2005 and PHPP¹⁶ using the average baseline figures for an 80m² semi-detached house (TSB, 2009, Ruyssevelt, 2011). A large number of the applicants used AECB's passive house technical standards in their energy design proposals (AECB, 2007:3).

Target	Primary energy consumption (kWh/m ² .yr)	CO ₂ emissions (kg/m ² .yr)	Useful space heating energy (kWh/m ² .yr)
SAP 2005 <i>(for RfF competition)</i>	115	17	Not specified (expected below 40)
PHPP <i>(for RfF competition)</i>	115	20	Not specified (expected below 40)
AECB's Silver standard	120	22	40
AECB's Passivhaus standard	120	No explicit limit (22-15)	15
<i>AECB's Passivhaus standard in the UK context</i>	<i>78</i>	<i>15</i>	<i>15</i>

Table 6: The CO₂ and primary energy levels for the RfF targets compared to AECB's technical standards (Based on AECB 2007: 3).

In Table 6, the whole-house CO₂ and primary energy targets are compared to AECB's passive house technical standards (AECB, 2007, TSB, 2009, Ruyssevelt, 2011). As Table 6 shows, the RfF targets are in some respects between AECB's Passivhaus standard and the UK context levels¹⁷, offering design flexibility to adopt solutions based on different buildings' condition and needs. A prescriptive version of AECB's energy standards gives clear guidance on what measures and technical specifications designers can adopt in order to comply with the aimed-for targets. Design guidance was also provided through Energy Saving Trust publications, giving technical guidance/specifications and design solutions on best practice refurbishment and high levels of energy efficiency performance (e.g. EST,

¹⁶ This selection was because SAP 2005 uses lower carbon intensities than PHPP and the proposed SAP 2009.

¹⁷ The Passivhaus standard, as specified by AECB, requires lower levels of primary energy consumption and CO₂ emissions for the UK context compared to the German standard requirements.

2009, EST, 2010b, EST, 2010a). These publications range from general whole-house refurbishment guidelines to more specific systems such as heating systems, guides for airtightness and efficient ventilation, and micro-generation, as well as technical specifications and implementation guides for insulation, windows and lighting.

The variation of refurbishment interventions in the RfF sample, include design solutions for mains gas, electricity or both; space heating solutions ranged from gas condensing boilers or micro combined heat and power (CHP) to heat pumps and other forms of micro-generation; renewable energy for space heating, hot water, cooling and electricity generation; other passive solar strategies and daylight strategies by increasing window size or by integrating conservatory extensions into the building; and natural and/or mechanical ventilation strategies with heat recovery. Airtightness strategies and solutions to minimise thermal bridges also vary according to the requirement for best practice with regard to the building's fabric. For all projects innovative design solutions are included. The improvements to the building fabric involved insulation (walls, roof, floors), windows and glazing systems, roof light such as sun-pipe solutions, doors, finishing materials (such as paints and claddings, carpet floor, laminate, etc.), and other design solutions or changes in building's layout (e.g. extension, porches etc.) affecting the overall building performance. In the sample the multiple technologies used make this study more complicated compared to other empirical studies focused on just one technology.

The selected sample of 26 properties in this study has been decided on based on two criteria: the geographical location and properties' building type. Properties' locations were selected within a maximum radius of 80miles from Oxford covering south east England to enable comparison between cases with similar weather conditions using the same heating and cooling degree days (Figure 37).

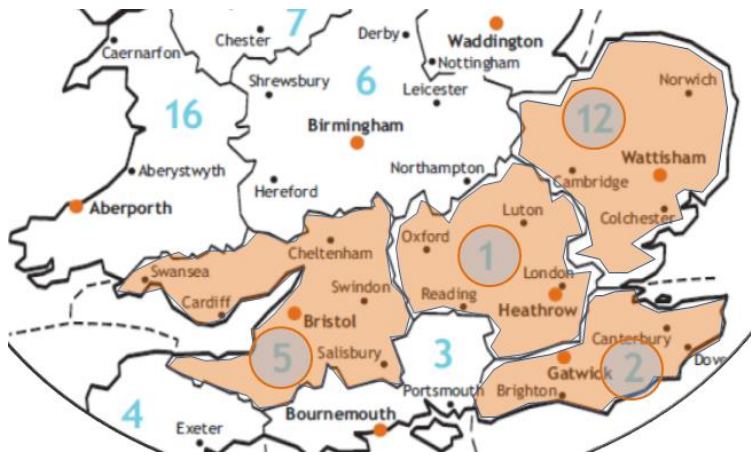


Figure 37: Degree day regions of the properties studied (Based on: CarbonTrust, 2007:5).

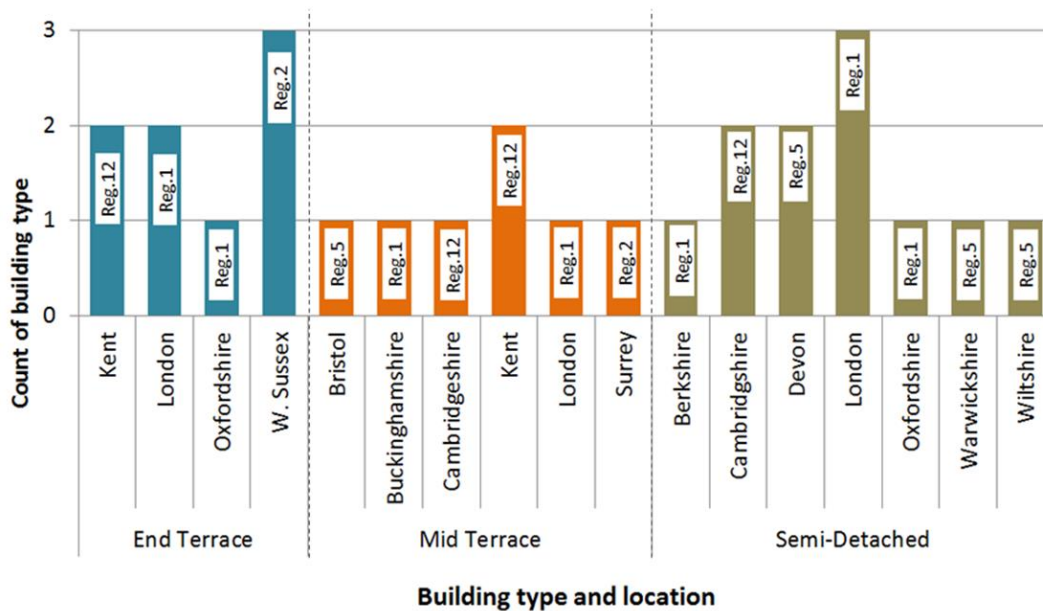


Figure 38: Property location, region id and building type (n=26 properties).

In this geographical area three building types have been studied: semi-detached, end-terraces and mid-terraces. Figure 38, shows the number and type of properties distributed in the selected locations. Most of the properties in the sample are located in Thames valley (n=10) and East Anglia (n=7) and a smaller number in South East (n=4) and in Severn Valley (n=5) area. The construction type of the buildings for the 26 properties in the sample is masonry cavity wall (n=13) followed by solid brick (n=6) within smaller number of other types of construction (Figure 39).

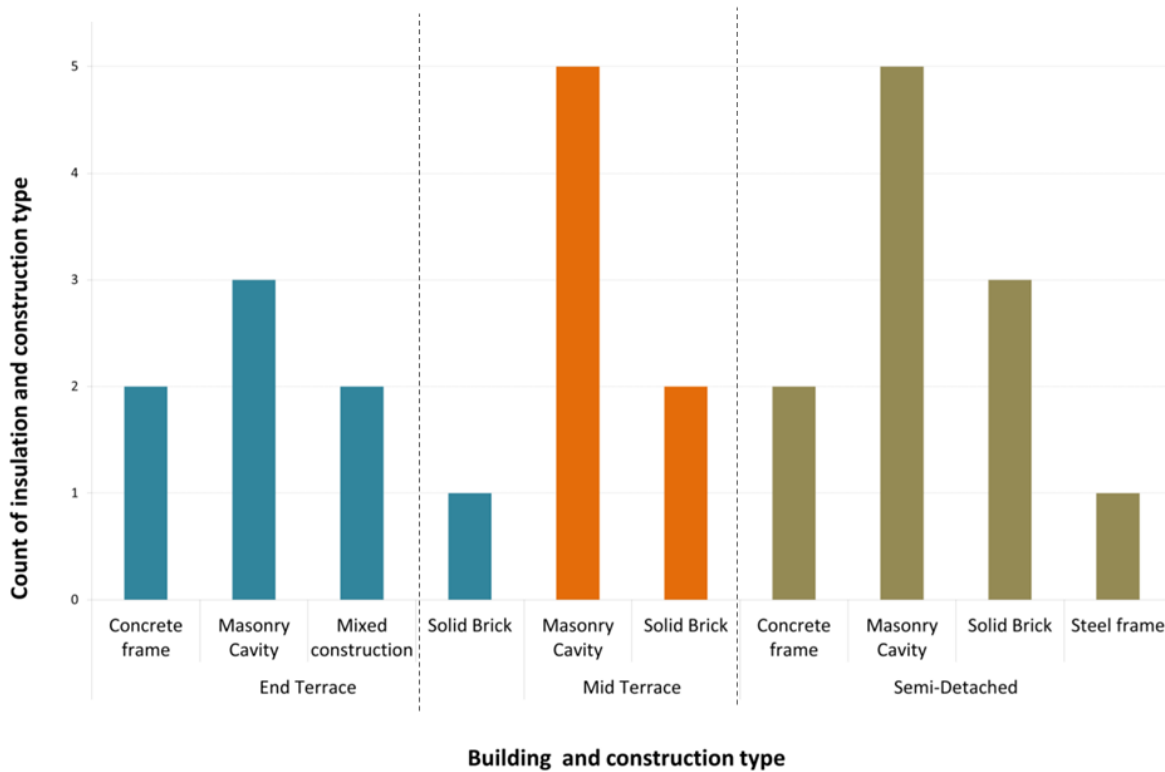


Figure 39: House type, construction type and insulation (n=26 properties).

The selection criteria were aimed at providing a degree of data homogeneity in properties to allow socio-technical interrelations to become more apparent and behavioural factors to be elucidated. Technical and non-technical characteristics of the sample are discussed in detail in following chapters.

Summary and discussion

This chapter discussed an interdisciplinary socio-technical approach to overcome disciplinary standpoints on complex interrelated socio-technical factors. An interdisciplinary mixed-method approach is suggested to explore these socio-technical factors related to occupants' interaction with low-carbon measures. Within this approach, interdisciplinary synergies and links between the different methodological and theoretical approaches examine household energy use holistically. The research design links the study's conceptual framework, research objectives, type of data, and methodological approaches of collection, analysis, and interpretation. This is supported by a conceptual

framework to connect elements from existing social theories, technical and socio-technical research and established methodological approaches, together guiding all the study's inquiry from the problem and purpose definition, literature review, and methodology, to data collection and analysis. In this design qualitative, quantitative and triangulation approaches are linked in all stages. An outline of the sample that the study has selected was discussed, providing an understanding of the key aspects considered in design and implementation for the study's research inquiry.

Chapter 5: Methods

This chapter presents the two main stages of the study's methodology design, the data collection and data analysis, which were developed in parallel during the design process complementing and informing each other. The study's mixed-method approach of data collection, the different types of data, the sources, together with the pre and post-refurbishment monitoring methods and techniques 'as designed' and employed by the study are presented in this chapter. Issues related to the association of this study with the RfF competition as well as administration and roles in the data collection are also discussed. The data collection design is followed by the study's mixed-method analysis design discussing the different analytical methods and techniques applied from the study to each of the data types presenting step-by-step the empirical analysis stages as implemented to explore the interaction of the low-carbon interventions and occupants.

5.1 Data collection design

Energy Saving Trust (EST) was appointed by TSB to handle the collection and aggregation of data encompassing monitoring and occupant experience evaluation from all Retrofit for the Future competition projects. A whole-house carbon and energy evaluation protocol was designed and undertaken by EST for the collection of the quantitative and qualitative data. This doctoral study having similar evaluation objectives to those of the Energy Saving Trust's evaluation process, has allowed the author of this study to: get involved and participate from the early stages in the consulting team, work close to EST's team and independent researchers (Databuild Research & Solutions) throughout the whole design process and carry out together with the appointed independent researchers the post-occupancy evaluation (POE) in the RfF properties. The study's interdisciplinary mixed-method strategy in the data collection design achieving its objectives to capture occupants' interaction in the low-carbon refurbished houses was entirely in accordance with the RfF

data collection design. This has allowed to a large extent the study's post-occupancy evaluation framework and all variables and determinants to be embraced in RfF's final POE design; whilst, in some aspects the study's more comprehensive examination of factors such as behavioural determinants of usage and control have been integrated collecting additional data only for the specific 26 case studies.

The data collection used a combination of 'short-term' measurements -one-time testing of the building fabric- and 'long-term' evaluation by monitoring overall building performance (TSB, 2009). Quantitative data included both 'short' and 'long'-term physical monitoring measurements, energy audits and spot testing such as thermal imaging and air pressure tests carried out at the different construction stages of the refurbishment process. In addition to the quantitative data, another crucial element of the evaluation of all RfF competition projects was the post-occupancy evaluation exercise appraising occupant experience in terms of the overall building performance and installed measures.

The qualitative data from the post-occupancy evaluation was retrieved by holding in-depth interviews with the householders and observational walk-throughs in the retrofitted properties. The design of the RfF post-occupancy evaluation was undertaken by Energy Saving Trust in association with a consulting group of academics (including the author of this study) and experts in the field of building performance evaluation studies. The Energy Saving Trust appointed Databuild researchers and a small number of academics, including the author of this thesis, to jointly carry out face to face in-depth interviews and POE walkthroughs in all RfF competition projects. Although the study conducted POEs in 30 cases in the south east England (out of the 119) only 26 cases had sufficient qualitative and quantitative data to be used for the study's analysis.

Data type (collected/ provided):	RfF	Study
Primary source		
Essential Information phone survey	√	<i>Provided</i>
Observations walk-by (external)	√	√ <i>Additional data collected:</i> Visual material, building environment external physical characteristics checklist
Observations walk-through (internal)	√	√ <i>Additional data collected:</i> Visual material, building environment internal physical characteristics checklist
Semi-structured interview	√	√ <i>Additional data collected:</i> Interview recordings, discussion observation notes
In-situ metering/spot checks		√ <i>Additional data collected:</i> Temperature, CO ₂ , RH metering in all occupied rooms
Secondary sources		
TSB Retrofit for the Future Database 1 year monitoring	√	<i>Provided</i>
TSB Retrofit for the Future Case studies Documentation	√	<i>Provided</i>
Modelling data (PHPP/SAP)	√	<i>Provided</i>
Building tests (e.g. airtightness, thermal imaging, etc.)	√	<i>Provided</i>
Degree Days Data		√ <i>Additional data source:</i> Heating degree days (Source http://www.degree-days.net)
Location data (Google map)		√ <i>Additional data source:</i> Orientation, aerial view, building context characteristics

Table 7: The types of data provided by EST/TSB and the additional data collected by the study.

Additional variables and determinants to the RfF POE objectives, both in primary and secondary data sources, were incorporated in the design and collected for this study's purposes. The different types of data either collected or provided to this study are summarized in Table 7 above.

5.1.1 Administration and roles in the data collection

The sharing of roles in the joint post-occupancy evaluation, with the author of this study having an academic role in the evaluation process and Databuild researchers the role of

interview leaders was mutual and complementary during the different stages of the process based on our experience and expertise in the field. Therefore, the main discussion in the in-depth interview, based on the semi-structured questions from the survey topic guide, was led by the Databuild skilled professionals in qualitative surveys; while the author's technical and POE expertise offered predominantly observational technical and behavioural insights in the survey process both in the interview and walkthrough stages. This role allowed this study to examine, analyse and interpret observations in areas such as the internal environment, building fabric, installed measures, controls and so on, as well as collect additional data and explicitly identify issues related to in-use post-refurbishment and interaction with technical change. The author's academic complementary role has also ascertained that all topics have been covered during the semi-structured discussion and that the data quality prevents significant omissions.

The liaison with the applicants and householders as well as administration issues of the RfF post-occupancy evaluation survey have been conducted by Databuild for all projects. This involved the recruitment of each occupant and collection of non-sensitive demographic information for the household (number of occupants, relocation background, etc.); also collecting information on the property and an outline of the refurbishment intervention in building fabric and measures installed from the applicants. This data for the 30 cases was provided to the author prior to the on-site evaluation, enabling comprehensive understanding and preparation of the observation list regarding post occupancy-evaluation for each case.

This sharing of roles was a parameter that has strengthened the study's data collection process, as it has offered the study the possibility to collect both qualitative and quantitative data of a significantly high quality. With this the study has also overcome other constraints found in studies of post-occupancy evaluation surveys when these are

carried out by a single person or by a pair of interviewers with the same disciplinary background or expertise (e.g. two architects, engineers or sociologists). These limitations often concern the degree and the quality of observational detail that can be collected during a one-off interview under the given limited time and without omitting information or breaking discussion coherence flow during the in-depth interview with the householder. Administration, costs, time and other constraints in building evaluation processes have been prevented in the course of this thesis due to the association with the RfF competition process.

5.1.2 Post-refurbishment monitoring methods and techniques

The data collection design employed a mixed-method approach bringing together methodologies from building performance (BPE) and post-occupancy evaluation (POE), households' social and physical survey methods using a variety of additional survey techniques (e.g. humidity, CO₂ temperature spot checks, pictures of technical details, etc.) to the RfF approach to elicit further comprehensive quantitative and qualitative energy use data. The methodological framework was designed to ensure that the technical aspects of the building and new measures, the occupant experience in the refurbished property after the installation process and their interaction are explored allowing socio-technical aspects to be evaluated concurrently.

The POE methodology process, involving a number of data collection stages 'on-desktop' and 'on-site', was designed and implemented as illustrated in Figure 40. The different types of methods (see Figure 40 and Table 8 below) like survey, tests, monitoring etc. undertaken before the visit allowed assessing, evaluating data and prepare the on-site stage process. The piloting survey allowed testing and evaluating the data collection process leaving space for improvements before the on-site main survey visit.

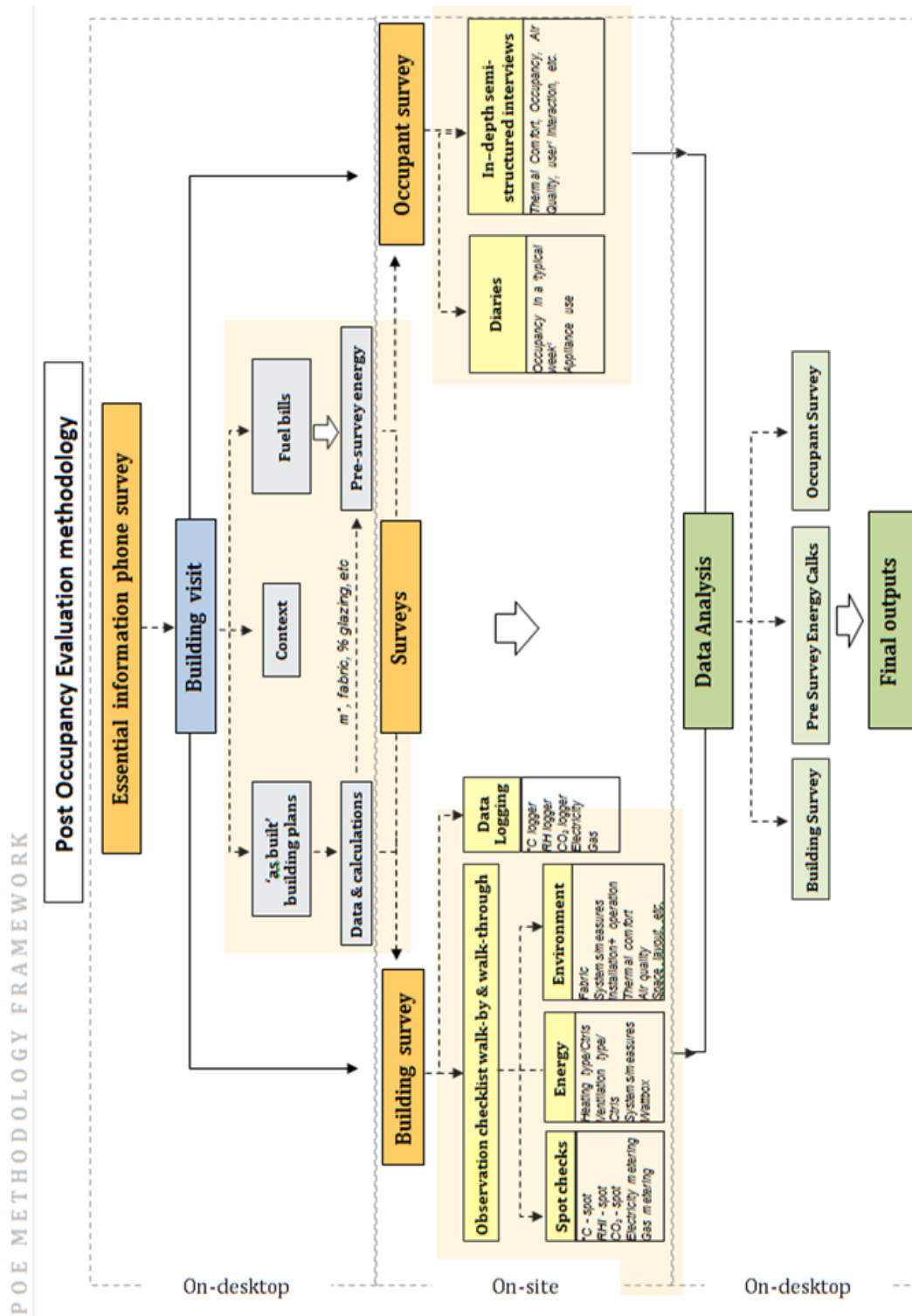


Figure 40: The different stages Post Occupancy Evaluation methodology framework developed for this study's objectives.

Data collection design: methods and techniques used in the RfF sample		
	Data collection design, methods and techniques	Intent and use
On-desktop	1. Essential phone survey information	Collect essential information on household, building characteristics and introduction of the on-site process to the occupants
	2. Pre-survey energy audit from fuel bills and meter readings	Evaluate households' overall energy performance pre and post-refurbishment interventions
	3. Fabric tests for 'as built' building fabric assessment (e.g. thermal imaging, pressurization tests)	Evaluate post-refurbishment interventions and installation from physical performance of the building fabric
	4. Post-refurbishment physical monitoring (data logging)	Understand and evaluate households' energy behaviour and buildings' physical performance
On-site	5. Piloting survey	Test and evaluate the design of the POE process and monitoring equipment on-site
	6. External walk-by observations	Collect visual and observation material and assess external building environment factors affecting a building's overall performance
	7. Semi-structured interview	Collect visual and observation material and assess indoor building environment conditions and factors affecting occupants interaction and a building's overall performance
	8. Internal walkthrough observations	
	9. In-situ metering/spot checks: external and internal temperature and internal relative humidity and CO ₂	

Table 8: Description of data collection design: methods and techniques used in the RfF sample.

The on-site methods using observational and social survey techniques, tools like audio recording, visual photographic material and spot checks allowed in-depth data to be crossed checked and triangulated and indemnify key interrelated factors in occupants' interaction that affect households energy use. Generally the combination of techniques has allowed greater reliability of the data collected, generated and provided to the thesis.

5.2 Piloting survey

The first stage of the on-site data collection involved testing post occupancy evaluation design approach in two semi-detached social house properties at Luton Borough Council refurbished to decent home standards including solar technology (photovoltaic) in the roof. Before completion, the main survey topic guide designed by the author of this thesis together with EST/Databuild was reviewed by an interdisciplinary 'expert panel'

consisting of experts in POE surveys and questionnaires design. The trial interviews were conducted two months before the RfF main survey leaving sufficient time for the administration of the interviews and for possible modifications and improvements of the POE process. The piloting allowed to take note of specific issues like on wording (e.g. instead of using ‘ventilate’ phrase it on ‘how often do you open the windows’), on the length, structure and roles between the author and researcher in the whole process (main semi-structured interview, walk-through and walk-by). It also allowed testing the monitoring equipment that specifically the study used for the spot checks making apparent some practical issues such as the data collection format that needed adaptation in this study’s observation check list. Despite the fact that the trial cases haven’t undertake the same deep refurbishment interventions or innovative technologies installed (e.g. MVHR), it has generally helped to amend some minor issues of the RfF designed process proving also that its design can be used to future similar studies.

5.3 Main survey design

The main survey design is consisted by the pre-visit survey design (on-desktop process) involving phone survey information and the pre-survey energy audits and by the on-site survey (on-site process) involving the building and occupant survey. The design of the on-site survey is structured by an in-depth semi-structured interview including internal walk-through and external walk-by observations (with the later external observations being this study’s additional data collection to the RfF competition and used only for this research analysis). The main on-site survey in each property lasted around 90 minutes allowing about 45 minutes each for the main interview and walk-through tour, and another extra 15 minutes before or after the visit in the property for the external walk-by. All 30 interviews conducted were recorded and 26 transcribed for analysis.

5.3.1 Phone survey information

Databuild researchers using phone survey in the RfF sample (on-desktop technique employing structured questions) collected essential information on households' characteristics. For the 26 cases used in this thesis the collected information was followed up by cross-checking with the documentation¹⁸ of each case used in the pre-visit preparation stage. The phone survey provided essential information: on the household (e.g. occupants' details, number of occupants and age, occupancy background occupants before and after work etc.); and basic information on building characteristics before and after refurbishment (e.g. building type, age, intervention measures and systems installed etc.).

This information allowed the author to familiarize with each case and the level of refurbishment intervention, and prepare observation points for the systems and measures installed. The study used cross-checking techniques to the essential information and documentation that offered some first inputs on possible deviations between the design proposal and the actual design implementation/installation of the low-carbon interventions (e.g. floor insulation or photovoltaic not installed due to the expense) before the on-site visit. The cross-checking has outlined also issues related to occupants' awareness on the measures and systems, as the information they provided by phone found not what was actually installed but on what occupants thought was installed in their houses. Also the phone surveys was a substantial element not only for the pre-visit preparation and cross-checking information, but also for introducing to the occupants the intent of the interviews' process, build a good rapport between them and the interviewees, and more

¹⁸ Documentation: is the report conducted by the project team for each project of the RfF sample that provides information on the project description (e.g. location, building characteristics type, wall construction, floor area etc.), design strategies planned occupancy, heating and ventilation strategies and other low-carbon refurbishment interventions) and on energy use (e.g. previous and estimated energy use). This is publically available from the 'embed' online database.

importantly saving significant time on explaining aspects involved in the onsite process the day of the visit.

5.3.2 Energy audits and energy assessment

The purpose of energy audits and energy assessment design, before the on-site visit, was to collect information on properties fuel bills (pre-refurbishment gas and electricity bills of at least one year), of the previous energy suppliers and tariffs for all cases. In particular for the cases that were the same occupants was to allow comparisons of energy use before and after refurbishment. Although the study was not able to have direct access to the pre-survey energy audit from fuel bills and meter readings ‘as designed’ due to the competition agreement the previous fuel use of a year was provided by the project team only in the documentation. The post-refurbishment fuel use for each property was collected and provided by the TSB Retrofit for the Future online database¹⁹. A first assessment of the physical monitoring in the post-refurbished properties was intended prior to the on-site survey, however very little monitoring data was available at the time in the RfF database. Energy use data forecasts using PHPP and SAP modelling tools were also provided by the properties’ documentation. Energy use assessment was not feasible in all cases in the sample for reasons of quality, quantity and availability of the pre and post-refurbishment energy data being an important limitation to the study’s evaluation approaches and energy assessment comparisons.

5.3.3 Building survey

Basic information on the building as discussed previously was collected from the on-desktop phone survey and properties’ documentation. The on-site data collection design using BPE and POE techniques consisted of:

¹⁹ The ‘embed’ online database Available at: https://est.amee.com/user_session/new [Accessed 19 Aug. 2014].

External walk-by observations: This is an important part of the on-site survey, designed and undertaken only for this study's analysis objectives, involving the data collection of visual material (photographic material) and observations (external building survey checklist) on the property's location (e.g. site position, surroundings, external building environment, orientation etc.) and on the building's technical characteristics (e.g. building type, number of storeys, external wall type and finish, roof type, openings' type, solar technologies etc.), (see Appendix 9). The purpose of this data collection is to evaluate the external condition of the building, measure installation and identify factors or in some cases occupants' interaction that can affect the overall building performance (e.g. trees blocking solar technologies, frequent use of the garden for family activities like standing cloths, children playing etc.). Aspects from the external observations related directly or indirectly to households' energy use were often picked up in the main interview survey enhancing the discussion with the occupants on their routinized practices.

Internal walk-through observations: This is the most significant part of the visit as it involves the occupant showing room-by-room the refurbishment interventions in the property, demonstrating measure-by-measure the systems installed and discussing their post-refurbishment experience living in the property. This technique allowed identifying: issues in the implementation of the design strategy, installation faults and omissions or variations from the 'as designed' proposal; allow perception-in-action issues to emerge such as occupant to demonstrate, interact and discuss about the actual use and control they have over heating and ventilation systems and with the other low-carbon measure installed. Similarly to the external walk-by the author designed an internal building survey checklist (see Appendix 10) that captures room-by-room occupancy and technical features. In this occupants were generally encouraged to show the interviewers physical issues that rose during the semi-structured discussion. By this the process complements the main interview

discussion as it allows observing occupants' behaviour, aggregate aspects on occupants' post-experience interaction, practices and routinised habits related to comfort and controls in the post-refurbished building environment.

On-site spot checks measurements: This was undertaken only for this study's analysis objectives capturing during the walkthrough the internal and external temperature, internal relative humidity and CO₂ levels on the day of the visit using data logger equipment (WatchDog A160 Temp/RH/CO₂ Logger). In all cases occupants were particularly interested and helpful in plugging in the monitoring equipment and participating in the process. The collected measurements complement the data from the semi-structured interviews and offer the option to cross-check occupants' doings and sayings. For instance when occupants asked to indicate their comfort level on a scale from 1 (much too warm) to 7 (much too cool) (see Appendix 11 interview scales) the room temperature spot measurement was used as an indicator to occupants' comfort. Also the spot checks were used as an indicator of issues affecting air quality as smoking habits, or a number of pets in the room during the visit adding more value and depth to the walkthrough observations. This type of data has allowed comparisons between sources and back up data source when long term physical monitoring values were not available.

5.3.4 Occupant survey

The occupant survey is consisted by the main semi-structured interview conducted by the Databuild researcher, the academic (author of this study) and the lead contact occupant (and ideally with other member of the household available on the day).

a. Semi-structured in-depth interview design

The occupants' survey conducted in two phases starting with the participants having an open question discussion as structured in the topic guide (see Appendix 11, 403) followed

by a tour in room-by-room and measure-by-measure walk-through discussion in the house. The interview commence with a brief introduction on the interview process (duration, explanation of walkthrough, photos, spot-checks etc. and confidentiality statement) and by tailored questions designed to confirm phone survey information eliciting basic quantitative information on occupants background (demographic information, occupancy, etc.). The main set of open-ended questions cover variables related to occupants' pre and post-refurbishment experience such as: likes and dislikes in the properties, indoor environment and comfort, heating and ventilation systems and controls; as well as socio-demographic variations in response to the measures (e.g. health and micro-factors) and behaviour changes related to the refurbished property. Two slightly different topic guides were developed one for the occupants that were living in the property before the installation works and one for new tenants to allow comparisons of variables between the pre, post-experience and also investigate issues related to refurbishment process and relocation. Another set of questions are on occupants' satisfaction and expectations of the RfF competition process (duration, disruption, cleanliness etc.) and with the handover/level of training provided for the new systems and the house as a whole.

An open discussion in the walk-through (room-by-room and measure-by-measure) explores variables related to occupancy, comfort, practices in heating and ventilation, overall environment and on aspects related to occupants' awareness and understanding of the measures installed affecting performance. These questions are mainly focussed on occupant's perceptions-in-action affecting energy use investigating the type of occupant's interaction and the frequency of use. The topic guide included also questions on the specific measures or systems installed (e.g. biomass, solar thermal panels, MVHR etc.) and controls encouraging demonstration. The semi-structured discussion closes with questions

on occupants' attitudes and beliefs in energy efficiency and environmental issues affecting behaviour and interaction with low-carbon measures.

5.4 In-depth interview selected techniques

The methods in occupant survey use a combination of qualitative and quantitative techniques collecting both types of data. The design using a topic guide approach covers all variables and overarching aims between this study and RfF competition objectives. In the topic guide design each core question is followed by a number of additional prompts that the interviewers used to encourage and follow up discussion on the topic when the respondent's initial answer was insufficient. The design of twofold questions looking both numerical and qualitatively on occupants' comfort, satisfaction, perceptions, understanding etc. used established scales from previous research in the field (see Appendix 11) to code quantitative responses allowing also qualitatively the occupant to explain the 'whys'. The interview process was to collect information about the household including except from the lead occupant also other members of the household to participate. This was an element that offered the benefits of capturing representative data on household members' perceptions, and their understanding and use of the measures installed. In this respect for instance it proved that the lead occupant may have had a vague understanding of the innovative heating controls but another member of the household have the actual control over the measure; or similarly have a different comfort level compared to other occupants that their comfort and ventilation practices were to open windows when he was not in the property. This has allowed this study to draw the picture of the household's energy use and occupants' control interaction in the property avoiding confusion when findings were not agreeing with lead occupant sayings.

Particularly effective in the semi-structured interviews was the interdisciplinary of the interviewers bringing different techniques in the process. In this respect the contribution of

the author in technical skills and experience in POEs was combined with social researchers' skills (Databuild) giving a broader approach in the data collection compared to single disciplinary approaches. This aspect was not only saved time to the interview process, but also has allowed balancing social and technical data bringing more in depth information.

a. Data collection 'as designed' and 'as implemented'

There were a couple of constraints in the data collection from how was initially designed by this study and finally implemented in association with the RfF competition. In the energy audits survey the study's design a comprehensive collection of the energy consumption from fuel bills for the pre-refurbishment stage that would enable a more detail understanding and comparisons of the pre and post-refurbishment energy use. Another aspect was that in the occupant survey design this study also initially included a small number from the interviewed cases (out of the 26 cases) to take part on focus groups involving free discussion on interaction with controls. From the interviews the cases emerged with particular issues in interaction with the new measures focus groups intended to elicit supplementary information on behavioural factors affecting interaction using semi-structured open questions and employing visual techniques and interactive methods. However, both these data collection procedures were not undertaken as this study could not have direct contact with the occupants of the RfF sample due to complying with the competition agreement; or in other cases due to the cost and time of techniques weren't allowed to bring more in depth data in the study engaging occupants in further procedures like focus groups as this was not part of their contract with the competition.

There was also factors related to the interview's administration time that was not only a delay factor for the 'as designed' data collection of this research but also unanticipated from the RfF competition process timeline. This was due to the lack of occupants'

engagement with the process proving very difficult to get hold of interviews despite their agreement with the competition. The lack of direct control of this study over the physical monitoring brought also some other constraints that were not initially considered by the study's data collection design, like for instance cases where monitoring equipment was moved next to thermal sources or unplugged. These aspects could only be triangulated by the odd data values, occupants' sayings and project team update.

5.5 Data analysis

The research design discussed in section 4.3 (Figure 33, p.137) illustrated the connections between research queries, data collection and analysis. In this section the sequence of the different steps undertaken in data analysis is outlined. The analysis explored the central phenomenon of interaction within three key areas distilled from the study's main research questions. The key three areas of the technical aspects (building fabric and systems), occupant (user) and interaction (energy use and operation) were used to provide the structure of the analytical process in which qualitative and quantitative empirical data were explored together. For different types of data different analytical approaches were used.

The intent of the analysis was to explore the interaction of the low-carbon interventions and occupants. Within the key three areas, factors affecting interrelations between variables and dependencies that were relevant to everyday practices of heat and ventilation interaction in the low-carbon retrofits were explored. Along with these the different stages 'as designed'/modelled, occupied and used provide the time sequence explaining how the building fabric and technology were designed, installed and used; who the occupants are and how their past, post refurbishment experiences were defined; and how (when) their practices fit (or not) the context of the design of low-carbon retrofit. The objectives of the analysis design are provided in **Error! Reference source not found..**

Analysis objectives (Pre-refurbishment and post-refurbishment/ In-use)		
A. Technical components of the building system		
1	<i>Pre-refurbishment ('as designed')</i>	▪ Define the level of intervention
2	<i>Pre, post-refurbishment ('as designed/built')</i>	○ Define the building performance (before and after the improvements)
3	<i>Post-refurbishment/ In-use ('as built/installed')</i>	○ Classify intervention according to the research question e.g. heating, ventilation, etc.
4	<i>Post-refurbishment/ In-use ('as built/installed')</i>	○ Identify to what extent the interaction is 'scripted' by the measures and interventions (technical perspective)
B. Non-technical components of the household system		
1	<i>Post-refurbishment/ In-use ('as occupied')</i>	▪ Define households' composition (socio-demographics)
2	<i>Post-refurbishment/ In-use ('as occupied')</i>	▪ Determine how the space is occupied by the occupants
3	<i>Post-refurbishment/ In-use ('as occupied')</i>	▪ Define occupants' experience in the route to learning about refurbishment interventions
C. Technical and non-technical (socio-technical) components of interaction		
1	<i>Post-refurbishment/ In-use</i>	▪ Establish how the space is defined by the occupants in terms of use
2	<i>Post-refurbishment/ In-use</i>	▪ Identify events of interaction
3	<i>Post-refurbishment/ In-use</i>	○ Identify the impact of the measure on the occupants
4	<i>Post-refurbishment/ In-use</i>	○ Identify to what extent the interaction is 'scripted' and what level of interaction is actually left to the users (user perspective)
5	<i>Post-refurbishment/ In-use</i>	○ Identify how occupants/ users operate- interact with building controls, technologies and systems
6	<i>Post-refurbishment/ In-use</i>	○ Identify frequency of interaction
7	<i>Post-refurbishment/ In-use</i>	▪ Identify practices (know-how and embodies habits/ institutionalised knowledge and explicit rules/ engagements and technologies)

Table 9: The objectives of the analysis design.

Objectives and sub-objectives in the table above were developed in line with the theories consisting of the conceptual framework and thesis research questions about interaction. Each of the different theories employed in the study has helped in formulating the objectives in each area and interpreting the result.

5.6 Data analysis design

The data obtained from different sources (see Appendix 8) consisted of long-term data comprising qualitative observations and occupant feedback, as well as quantitative monitoring physical measurements; also used was short-term data including quantitative

spot check measurements and fabric performance tests. The three types of data (or items of analysis) either collected or generated include: textual data of narratives, transcriptions and observation notes, and different formats of documentation texts; visual data with images, pictures and graphs; and finally numeric data of different units varying by type. Using these types of data, qualitative and quantitative analysis was used to quantitatively explore physical performance determinants and qualitatively examine occupants' perspectives and interactive perspectives-in-action. An overview of the analysis structure with the different analytical methods and techniques applied to each of the data types is provided in Figure 41.

The process of conducting analytical methods involved becoming familiar with the different types of data. In this regard all 26 recorded interviews, consisting of an open-ended discussion and walkthrough, were transcribed by the researcher. All transcribed discussions were analysed thematically (e.g. building, occupant and use), at the level of each single case, to identify the main relevant themes that emerged within the a priori categories of the semi-structured interview guide. This was followed by a comparative analysis of the themes identified from all the cases in the RfF sample, using text analysis software (NVivo).

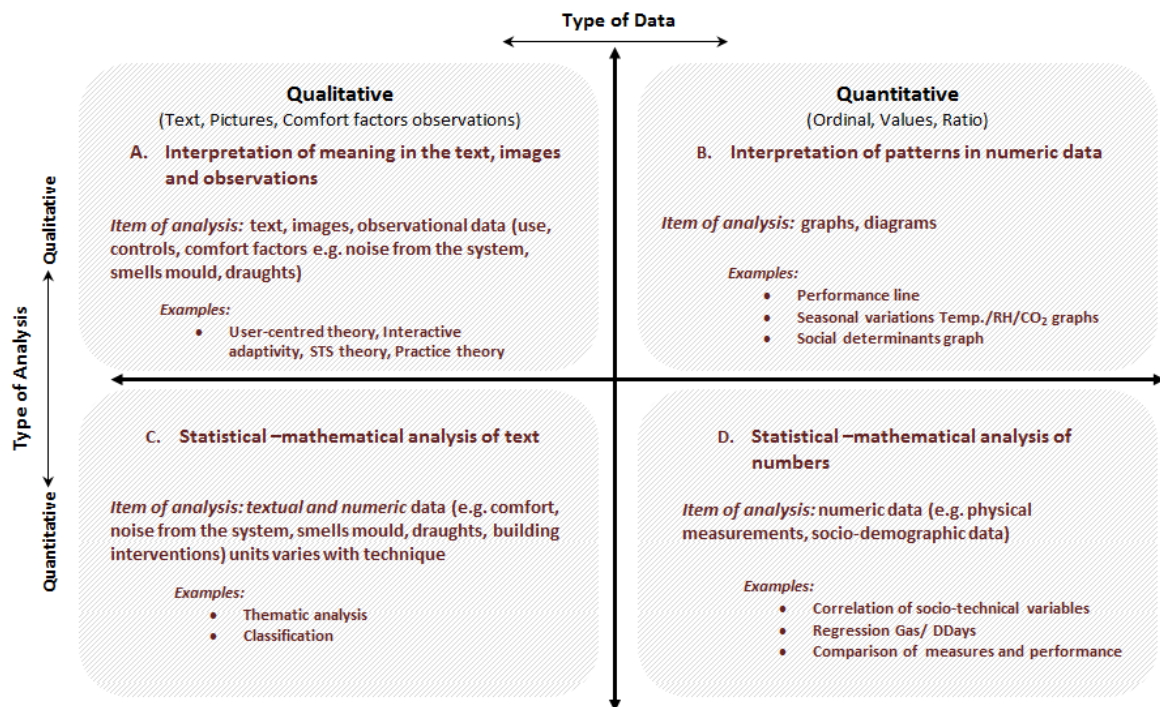


Figure 41: Mixed-method analysis design (adapted from Guest et al., 2012).

The thematic approach was also applied to the observational data from the walkthrough/walk-by consisting of textual data on occupants' demonstrated practical use of the building environment and measures ('perception-in-action'), as well as by narratives on their perceptions of operations and controls. Quantitatively oriented analysis approaches were also used in interviews' textual and numeric qualitative data. These approaches have helped to evaluate the frequency of the repeated themes and observable variables in the sample; from the co-occurrence of specific words (or phrases) key issues and repeated ideas associated with a household's interaction and energy use were also identified.

Classification approaches were applied to the qualitative and quantitative data by evaluating the level of intervention in terms of the building fabric (passive or active measures) and the interaction of passive or active users. Mathematical analysis of the numeric data (e.g. gas consumption, internal temperature and occupancy) was necessary to identify factors in the building performance, occupants' interaction and external

environment, as well as underline correlations between socio-technical variables that explain patterns of occupants' interaction with the low-carbon measures. Despite the small number of properties in the study's sample statistical analysis software (JMP, Excel Power Pivot) was used for exploring correlations between variables and to allow comparison between sets of variables. Qualitative (QUAL) and quantitative (QUANT) meanings of occupants' actions and statements on heating and ventilation from this analysis were triangulated; for the interpretation of findings theories from the conceptual framework were used to explain interaction practices in the low-carbon retrofitted households.

5.6.1 Thematic analysis

Methods of thematic analysis allowed identifying, analysing and reporting themes or patterns within the three key areas of the empirical data, related to the building, the occupant and the interaction between the two. According to Braun and Clarke (2006):

A theme captures something important about the data in relation to the research question and represents some level of patterned response or meaning within the data set.

Themes or patterns within the data were driven by the thesis's theoretical interest in the topic of occupant behaviour with low-carbon measures, but using a more explicitly analysis-driven approach to the interaction. The main overarching themes were drawn a priori, in relation to previous literature and studies in this area and in line with the study's interview guide. The analysis has used semantic classes' investigation (e.g. phrases, clauses meanings of occupants' sayings from the interviews) into the data content, from which sub-themes emerged showing correlations between variables. When a factor was identified as being an important casual variable of the correlations by which this factor affects the outcome of interaction and the energy use (e.g. windows operation and pets in a room increasing CO₂ levels) were then investigated further. Codes were developed to

represent the identified themes and sub-themes, and link raw (primary) numerical data for later analysis (Appendix 8).

A threefold analysis of components was developed for each individual case in the RfF sample. A preliminary analysis in each area (building, occupant, interaction) has allowed first the identification of key issues within these topics. Specifically, correlations between technical variables of the building and non-technical socio-demographic and economic factors of the occupants have specified the background for each in household system. This was followed by an integrated analysis of the correlated socio-technical factors to explore occupants' interaction with heating and ventilation energy use in the low-carbon households. The analytical considerations of the content and the analysis of the key components for each group are discussed as follows.

5.6.2 Technical components of the building system

The themes and sub-themes identified in relation to the building include variables related to the building context, building fabric and building system characteristics (Appendix 8). The building context was defined by a range of non-interactive variables and parameters such as building age, type floor area and space layout, etc., and by the external climate system including building orientation and external temperatures. The analysis has explored first the ways the technical factors in the sub-themes have influenced the 'as designed' proposals, for instance how conservation area restrictions might have affected the design choice of a window or installation of solar systems on the roof. Then, it has explored from a technical perspective the extent technical changes and improvements in the building (e.g. the size, layout or increased amount of wall insulation) may influence the ways occupants interact with the space and operate systems (e.g. glazing system).

It was also important from the preliminary analysis to set up the base case building status by exploring and understanding the building prior to the low-carbon works and installation of systems. This underlined the problematic issues in a building's performance, giving insight into what led to the proposed type of refurbishment intervention and selected design solutions. This has also provided the background for the next steps of analysis that helped understand the occupants' transition from the previous building environment to the refurbished one, along with the extent of its influence on occupants' behaviour and interaction with the new building system.

The variables related to low-carbon measures and technologies, in terms of the building fabric and building systems themes, were determined from a clear technical perspective to represent the different levels of the refurbishment interventions in the sample. Mathematical analysis of textual and numeric data for these variables was used to evaluate and classify the level of intervention in the building and assess the predicted performance of the designed low-carbon interventions. Through this analysis not only the 'as designed' and 'as modelled' intervention approaches were explored, but the baseline for the as installed and in-use evaluations was also provided; these were used in the following steps for further comparisons between actual and predicted performance of the household system.

Using thematic analysis a key variable was extracted from the data in the building systems theme, affecting the 'as modelled' and in-use considerations, concerning the performance of combined systems. In particular, the sample was found to include low-carbon systems that tend to perform not as one combined integrated low-carbon solution but as separate individual systems. For example, system performance explored the level a boiler and solar panel system (or a CHP and an intelligent control system) can perform efficiently together as one system for hot water. Of great significance in this analytical approach was

identifying whether the performance of a system depends on its specifications, installation or user operation. In the next steps of the analysis these factors have been of particular importance as they allow exploration of what type of changes in the building environment are correlated with occupants' behaviour change and households' energy use practices. Technical aspects were explored also within different groups. For example, in groups of occupants (the same occupant or different occupants before and after intervention) first the extent to which technical changes are correlated with behavioural factors (internal influences such as habits, awareness, routines, etc.) was identified; then the extent measures control and operation were determined by external influences such as technology, installation services, etc.; and finally the patterns showing how occupants' interaction and performance of the refurbished house are affected by these changes were explored.

5.6.3 Non-technical components of the household system

Focusing on the occupant, socio-demographic and economic themes as well as occupancy patterns were drawn a priori, while sub-themes were extracted from sample analysis (see Appendix 8), to provide for each household in the sample an occupancy profile ('as occupied') before and after refurbishment works. At a household level the analysis has explored issues beyond the existing literature and underlying correlations between the non-technical data (or social data, e.g. number of occupants, age, income, etc.) and energy use; but it has also looked at relationships within occupants' variables related to a household's recent changes. For example, changes related to financial status, health condition or family composition were primarily analysed in terms of how these can affect one another and then in relation to other areas. The analysis has focussed on the extent these variables affect an occupant's interaction with the building environment and energy use, investigating for

example if a change in an occupant's health condition can be directly correlated with the occupancy patterns affecting (or not) a household's energy use.

Example of distinct groups emerged within the occupancy theme when looking at who the occupants are, in terms of being different or the same before and after the refurbishment, and occupants' relocation status, in terms of living (or not) in the property during the refurbishment works. Occupancy variables were found of particular importance as they provide the time frame in which interactions occurred. These occupancy factors then were analysed in relation to interaction factors, such as comfort, usage controls and energy consumption, by exploring occupants' actions and statements triangulating numerical and textual data. Direct correlations between occupancy factors and occupants' past and post-experience in the property related to behaviour change variables were explored in depth in a household's interaction analysis.

Another non-technical factor that emerged from the analysis, related to family composition, was the role of each occupant within a family or within a household as concerns the operation of measures and system controls. Thus, distinct roles between occupants, assigned as the carriers of specific controls and interactions, in the household were also explored. The examination of these roles helps in understanding the socially determined responsibilities of the individuals within the family and the lifestyle of the household interacting with the building environment. Some other aspects that emerged that were correlated with demographic and occupancy factors were the allocation reasons often related to occupants' health issues and family composition (i.e. mobility issues or single parent families).

5.6.4 Socio-technical components of interaction

At this level the analysis has looked at correlations between variables within the major themes and sub-themes of the building, occupant and interaction (see Appendix 8). It should be noted that the analysis of users' interactions with technical parts focuses on the post- refurbishment in-use stage and considers as the building environment the status the building has when delivered from RfF design teams to the social tenants. In this respect the interaction is explored only with white goods and miscellaneous appliances in the building environment; whilst occupants' interaction with brown goods is not part of the study's analysis. This argument is supported by ownership status, which in previous studies (e.g. Shove and Pantzar, 2005) has been considered a significant social determinant of occupant behaviour diverging from the perspective of autonomy in terms of personal choices (e.g. level of technical interventions, level of selection of space or household equipment). In this respect, the analysis has not considered occupants' participation in major choices, as concerns the retrofit design process or systems selection, for the reasons that such aspects are not anticipated for social housing tenants.

The key factors identified in occupants' analysis were then viewed in regard to the past and post-experience with the building, focussing on interaction factors that emerged from the data such as control and comfort, satisfaction, energy behaviour and awareness. Occupants' past-experience in the property was used as a benchmark in the analysis for assessing changes in occupants' opinion of the property or in their perceptions of energy efficient behaviour after refurbishment works. The analysis has taken into account the distinct groups that emerged in terms of occupancy and examined them in relation to occupants' personal values, level of awareness and engagement in supporting the process. Their perceptions of the retrofitting process have shed light on other intervening factors related to occupants' satisfaction with the process, such as works duration, level of

disruption, relationships and communication with the project management and construction team. These factors were examined in relation to occupants' expectations of the process, level of participation and design choice provided, as well as their experience in the route to learning controls, operation and maintenance of the low-carbon interventions. Occupants' awareness of household energy costs was examined in relation to occupants' levels of comfort and income together with their understanding of controls of the building fabric and systems pre and post-refurbishment. The handover process and the training provided for the installed measures were assessed in terms of the person providing information ('housing officer'), the type of training material and the time that they took place. Exploring these factors has helped the author understand to what extent occupants' knowledge of low-carbon measures in the building is due to the instructions and training provided (explicit knowledge) or due to occupants' personal experience, perceptions, insights, and know-how (tacit knowledge) (Darby, 2006). Similarly this has also allowed identification of the ways knowledge and beliefs can lead to specific actions and practices affecting heating and ventilation interaction.

All these factors were explored first at the level of the individual and then at the household level as a whole. To explore events of interaction within each household, the analysis has taken into account that occupants are carriers of practice of the indoor climate regulation (Gram-Hanssen, 2008), performing different 'doings' based on their physiological comfort and behavioural and psychological adaptation (Liu et al., 2012a) to the post-refurbished environment. In this respect a key point in the analysis was the extent the interaction²⁰ was 'scripted' or prefigured by the low-carbon measures and interventions. Technical and behavioural variables, as will be discussed in section 5.6.5.1, involved in heating and

²⁰ The study has considered interaction of the user with technical parts at the state the building was when delivered from stakeholders (e.g. social house providers and design teams) to social tenants; a building system includes interaction only with white goods and miscellaneous appliances and excludes interaction with brown goods.

ventilation practices were evaluated in terms how ‘scripted’(prefigured) or ‘user controlled’²¹ the design of the measures is and passive or active users are; as well as how the layout and space prefigures (or not) occupant comfort, interaction and practices involving the indoor environment. The analysis design in the following section involves evaluation of the factors that are related directly (or indirectly) with interaction (occupants’ full or null control) and energy use.

5.6.5 Determinants’ evaluation and classification

Thematic analysis was used to organise and describe the dataset in rich detail within all three key areas and identified themes. Then evaluation and classification of the data was employed to relate a certain element (or attributes) to a group (or class). Physical-cognitive classifications like sorting for instance the low-carbon heating system by the user controls provided or relating for instance particular heating system controls to a set were undertaken in the data analysis.

5.6.5.1 Levels of interaction

As regards the building, in preliminary analysis, physical determinants were evaluated and grouped based on the level of interaction (if any) between the technical factors (or variables) and occupants. Physical determinants associated with the building context and building fabric were defined in this study as non-interactive technical factors (or determinants), due to their zero to low interaction with the occupant/user. In this respect the study considered building context factors such as the building age, type or physical fabric attributes such as walls’ technical components (*U*-values) that have limited or no direct interaction with the occupant. Thus, the medium to maximum level of user

²¹ The study uses the term ‘scripted’/prefigured to describe measures, systems and controls that designed for passive users and involve null interaction with them (non-interaction), opposed to the ‘user controlled’ which are designed for active users and involve some level of interaction.

interaction corresponds to the technical variables that allow interaction of the occupant and are correlated with user energy controls (see Figure 42).

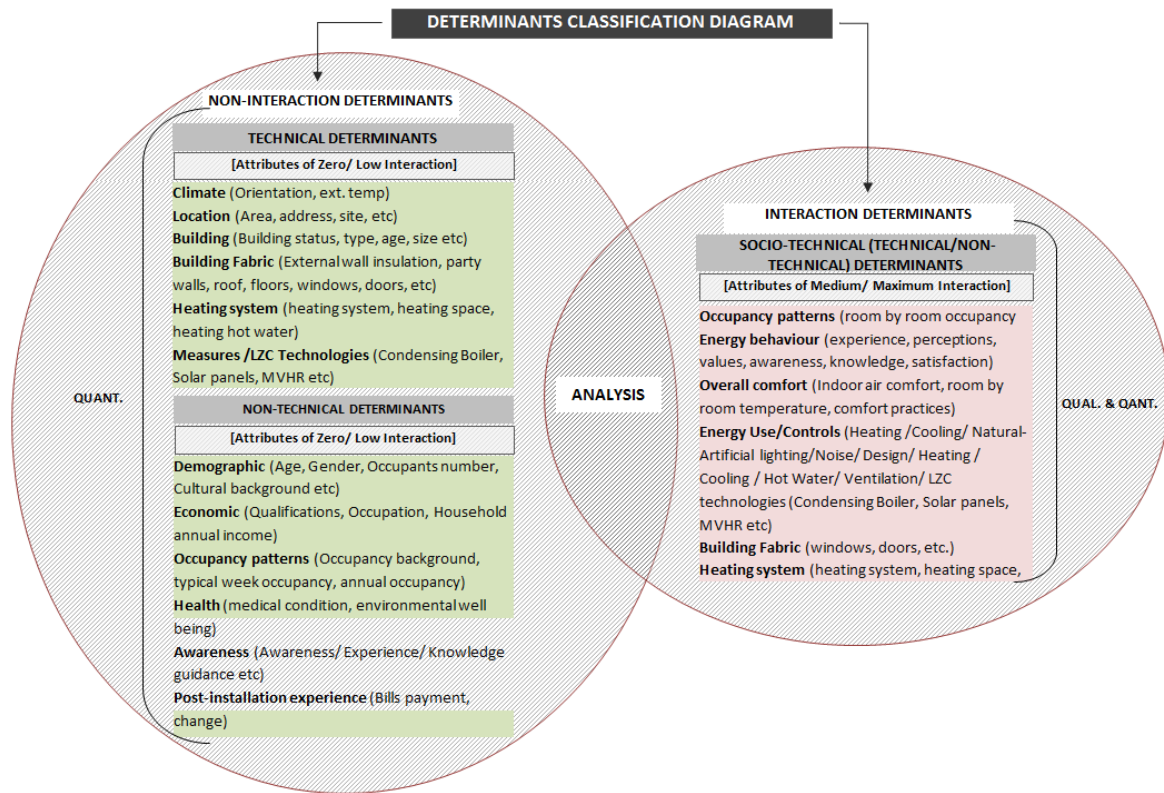


Figure 42: Classification of technical and non-technical determinants of occupants' interaction.

Once the technical interventions were classified based on the level of occupants' interaction, the interaction was examined at the level of control left by the measures ('scripted' or prefigured) to the users for heating, ventilation and hot water. The measures (fabric, systems and controls) were evaluated in terms of how 'scripted'/prefigured (or not) their overall design is; what level of interaction after installation is left to the user (full interaction/control, no interaction/control); and finally how passive or active user(s) are in the 'household system'. The evaluation uses a scale²² of interaction (1=Full interaction/control, 5=No interaction/control), defined by the control a user has over a measure and developed in this study to explore the research objectives (see an example of classification in Table 10 below).

²² Scale of interaction/control: 1=Full interaction/control, 2=Good, 3=Mixed, 4=Poor, 5=No interaction/control.

For example level 1 of occupants' interaction is when they have full control over the heating programmer understanding completely how to operate it regulating temperature to their comfort as well as being fully aware of how their behaviour could affect heating system performance. Whilst, a 5 level of no interaction means for instance that the programmer never changed to occupant's preference because they don't understand and know how to control it (see Appendix 6). Users have also been classified as active users when they have control over a measure or a system and passive users when they do not have any control. This classification allowed evaluation of whether the level of interaction is prefigured by the technology and measure or by occupants' (users') practices. This type of evaluation analysis was used in all cases in the sample to allow comparisons between system controls and occupants' interaction in heating and ventilation.

Systems and measures ‘as designed’

System operated ...		Directly/ Indirectly	Via measures	Controls designed for...	Level of interaction with the measure	
Heating						
Space	Gas Boiler	Direct	Gas boiler controls	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
					<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>
			CHP boiler controls	<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>	
			Heat pump boiler controls	<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>	
	micro-CHP	Indirect	Programmer	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
			Thermostat	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
	Heat pumps	Indirect	Intelligent control systems (Wattbox, Optima Design Controller)	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
	Biomass		TRVs Storage heater controls	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
Hot water	Gas boiler	Direct	Gas boiler controls	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
					<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>
			CHP boiler controls	<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>	
			Heat pump boiler controls	<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>	
	Heat pumps	Indirect	Biomass boiler	<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>	
			Solar thermal controls	<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>	
	Biomass	Indirect	Programmer	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
	Solar thermal		Intelligent control systems	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
Ventilation						
Natural	Windows	Direct	Window operation	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
			Door operation	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
	Doors	Indirect	Windows’ trickle vents	<i>Active users</i>	<i>No interaction/control (Lev.5)</i>	
			Doors’ undercut gap	<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>	
Mechanical	MVHR	Direct	MVHR unit controls	<i>Passive users</i>	<i>No interaction/control (Lev.5)</i>	
			MEV fans ON/OFF	<i>Active users</i> <i>Passive users</i>	<i>Full interaction/control (Lev.1)</i> <i>No interaction/control (Lev.5)</i>	
	MEV fans	Indirect	Control panel	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
			Boost button	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	
			Air valve controls	<i>Active users</i>	<i>Full interaction/control (Lev.1)</i>	

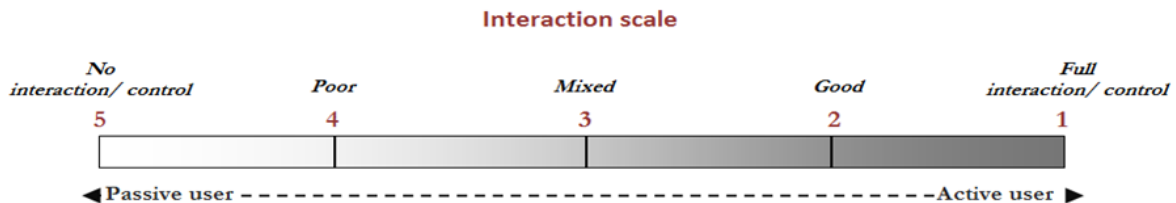


Table 10: Hypothesis of classification of occupants' interaction with heating and ventilation measures as design intended.

Considering the above the study discusses in Figure 43 below an illustrative case that exemplifies the previous approach focussing on the analysis of buildings' air quality. Therefore, the air quality and occupants' interaction with ventilation was explored by

looking first at the range of ventilation types in the properties. The main sources of ventilation in the sample were the natural ventilation (‘passive ventilation’) and mechanical ventilation (‘active ventilation’ involving MVHR or air extraction fans), and combination of the two.

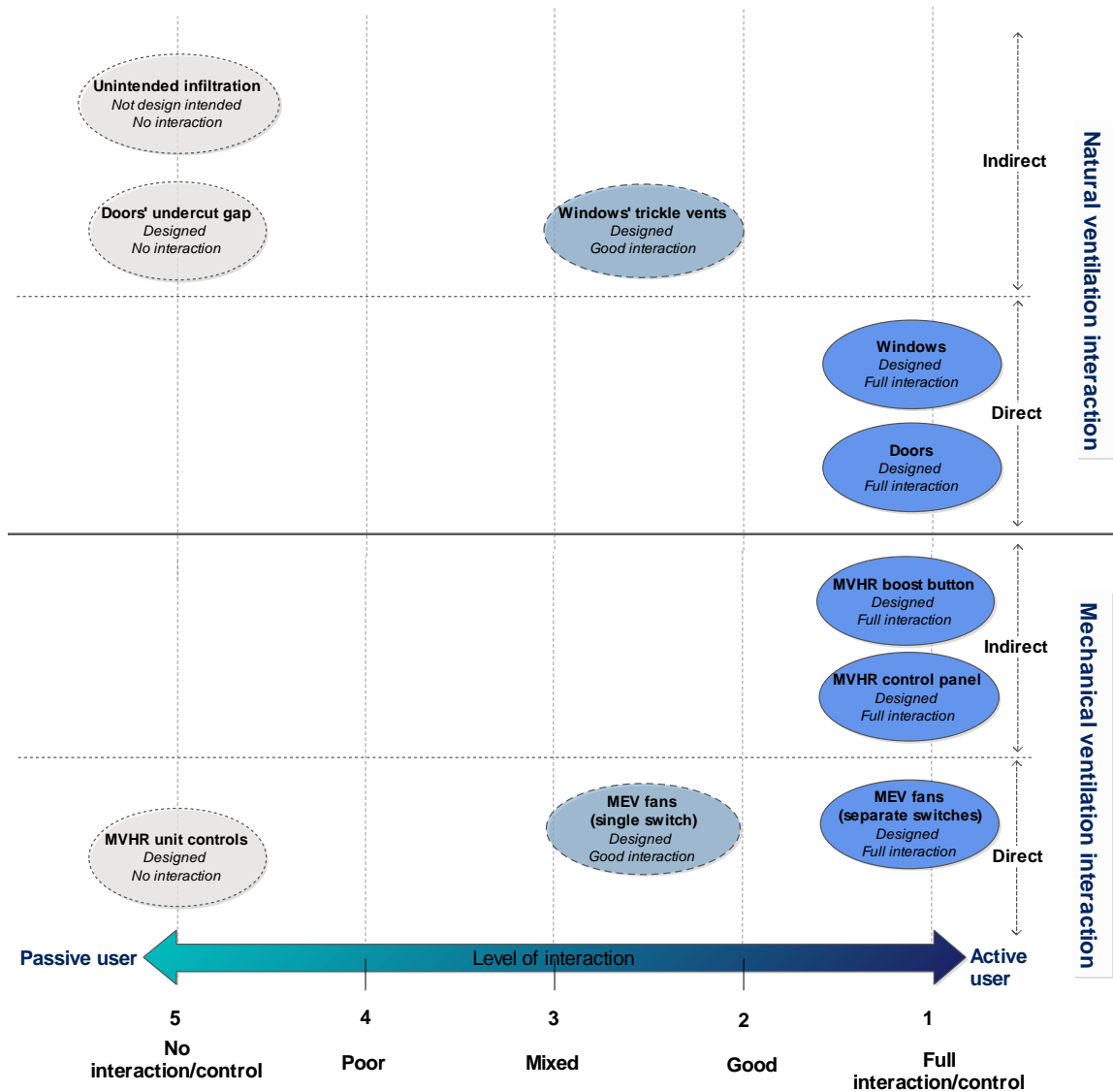


Figure 43: Example of the study's hypothesis on the influence of the ventilation systems and controls on users' interaction as design intended.

The analysis has looked at the two main sources of natural ventilation: controlled, through openings of windows, doors, windows' trickle vents, and door undercuts; and the uncontrolled by infiltration through unintended openings in the building fabric and between building components. Mechanical ventilation sources in the sample were

mechanical ventilation with heat recovery or an extraction system with fans for the wet rooms (kitchen and bathrooms).

Following the evaluation process discussed previously, the analysis has looked at the level at which interaction is ‘scripted’ by the ventilation measure, the level of interaction left to the occupant (passive or active user), and also the actual performance as measured by the value of this interaction (e.g. CO₂ levels). The actual performance was assessed against the current standards for CO₂ levels and humidity discussed in the following sections. Thus, from the preliminary analysis of the data the hypothesis developed about natural and mechanical ventilation and user interaction is illustrated in Figure 43 above. In the study’s analysis the hypothesis used, took into account all types of ventilation included in the sample ‘as designed’ to be used, exploring part of the study’s query about ventilation by evaluating the level of interaction left to the user (prefigured/ ‘scripted’ or not by the ventilation system). This is then followed by a comparative analysis of practices and systems, as discussed in the next sections.

5.6.5.2 Physical evaluation of indoor comfort

For each property the indoor conditions were evaluated using mathematical analysis of internal and external temperature, relative humidity (RH) and CO₂ levels of the high occupancy rooms (e.g. master bedroom, living room, kitchen, and main bathroom). The findings for each case in the sample were evaluated against national standards for dwellings and previous studies of comfort in UK houses. According to health standards and wellbeing the recommended lowest comfortable indoor temperature for heated rooms was suggested between 18°C and 21°C (typically 21°C in the living room and 18°C in bedroom spaces) (EST, 2012, Kane et al., 2011). Factors related to the indoor space analysed in terms of occupancy (e.g. high/ low occupancy rooms, type of activities that

occur in the room) were then evaluated against the actual temperature in the rooms (spot check and monitoring measurements) and occupants' comfort factors.

In order to analyse the actual performance of the indoor air quality in the retrofitted homes evidence from previous research (CIBSE, 2005, BS5250:2002, 2005) regarding concentrations of CO₂ levels and moisture (relative humidity RH) were used as benchmarks (Table 11).

	Source	Indicator	
Carbon dioxide (CO₂)	<i>(CIBSE Guide B, 2005)</i>	800-1000ppm	Adequate air quality indicator
Relative Humidity (%)	<i>BSI BS5250:2002 (BSI 2002)</i>	40% - 70%	Specified level above which condensation and mould appear

Table 11: Standards for CO₂ and relative humidity in the UK.

The indoor air quality is dependent on several parameters related to the exposure of an individual to numerous pollutants present in a space, such as moisture, volatile organic compounds (VOCs) and CO₂. These pollutants arise from household activities such as cooking, cleaning and heating, or other occupant activities such as smoking (BRANZ, n.d). The concentration of pollutants depends on parameters over time such as the emission rate of a pollutant, the ventilation rate of a space and their concentration in the air ventilation (Bluyssen, 2009). The focus of this study was only on two pollutants: the CO₂ and moisture. Hence, according to CIBSE Guide B (CIBSE, 2005:2-15), within the UK, a CO₂ level of 800 to 1000ppm is often used as a good indicator of an adequate ventilation rate in a building, which would appear to equate to a fresh air ventilation rate of 8l/s per person (0.5–1 air changes per hour rate (ACH). As regards moisture according to British standards properly ventilated domestic buildings should control the humidity of internal air to between 40% and 70% (BS5250:2002, 2005).

Additional aspects considered in the analysis of the indoor environment and MVHR systems were the ease of maintaining comfortable conditions looking at the even distribution of the heat throughout the house and the cold spots that booster fans might provide over a year. Technical factors related to noise levels, smells and excessive dust from the MVHR were also examined in relation to occupants' satisfaction with the measure and comfort levels.

5.6.5.3 Classification of the level of refurbishment interventions

The technical data of the building system was also explored based on building type and level of intervention. Two main groups of building type emerged from the sample based on similarities in terms of building fabric performance; thus the first group includes semi-detached and end-terrace properties, and the second mid-terraces. To understand the analysis of the building system performance after the refurbishment works it was important first to classify the level of intervention of the low-carbon improvements undertaken in each house in the RfF sample. This involved grouping the low-carbon improvements made over the building fabric and systems in relation to their level of compliance with current UK standards (Table 12).

The aim of this evaluation was not only to establish the level of intervention for each refurbished case in the sample, but also to contribute in the field by moving beyond the current inconsistency in overarching terms in describing refurbishment design processes and low-carbon interventions (as discussed previously in Chapter 3, section 3.1.2).

Level of intervention		Low-carbon improvements description	Complying with standards and methods
(DR)	Deep Refurbishment (or deep retrofit)	Insulation (floor, wall, loft, windows), space and water heating system, daylighting, ventilation and space cooling, renewables energy generation, passive strategies, thermal bridges and airtightness strategies	AECB standards (Silver and Passivhaus), Eco-Homes methods
(TR)	Typical Refurbishment (or typical retrofit)	Insulation (wall, loft, windows), space and water heating system, ventilation, lighting and airtightness strategies	Between AECB standards (Silver) and Approved Document L1B–Existing Dwellings Building,
(BR)	Basic Retrofit (or basic renovation)	Insulation (wall, loft), space and water heating system, ventilation, lighting and airtightness strategies	Approved Document L1B–Existing Dwellings Building, Warm Homes standard, Decent homes standard

Table 12: Classification of the level of refurbishment interventions in the RfF sample.

For instance, often under the commonly used title of ‘deep refurbishment’ the type and level of interventions can vary significantly, creating confusion between what the title implies and what the actual level of intervention is. This has also enabled comparison between the ‘as designed’ proposals and current refurbishment standards, but most importantly numerical comparison and evaluation of the ‘as modelled’ performance (see low-carbon standards in Section 4.4.2, Table 6: p.147) actual performance of the household (in-use).

5.6.5.4 Climate and heating energy performance

Mathematical analysis was used to evaluate a building’s actual energy performance and examine the dependencies in heating energy use. One of the factors affecting heating energy consumption relies on the external weather related temperatures (climate). The rate of a building’s heat loss is directly related to the difference between the inside and outside temperature; in this respect the heating consumption is directly related to the degree days

for a specific region. Hence, climate and property location have put the margins in grouping the study's RfF sample in four different regions (see marked regions in Figure 44), based on the degree day data.



Figure 44: Degree days' regions and reference site of the properties studied (Thames Valley (1), South East (2), Severn Valley (5), and East Anglia (12)), (Based on: CarbonTrust, 2007).

The degree days were used in a building's performance calculations after the low-carbon interventions. The study uses a building base temperature of 10 degrees recommended for thermally well insulated buildings with large internal gains (ECI, 2012). The analysis uses graphical representation the slope of the plot of energy use against degree days (performance line) to appraise the low-carbon improvements in the building (e.g. how well the building was insulated or heating system response), as well as detecting other energy waste related issues, heating system faults and inefficient 'doings' on a household's heating management. Another group that emerged related to the performance was the fuel type; therefore, two fuel heating types were used by low-carbon systems in the sample, gas and electricity. These factors were taken into account for the comparison analysis of heating system performance between cases, as discussed in the following sections.

5.7 Data analysis methods and tools

The study has used tools such as JMP version 10.0 (2012) of SAS Institute and Power Pivot for Office Excel for statistical analysis of the quantitative data; whereas NVivo version 9.0 (QSR International, 2010) was used for the analysis of the qualitative data. An SQL Server database was used to analyse relationships and queries between the different tools and data sources.

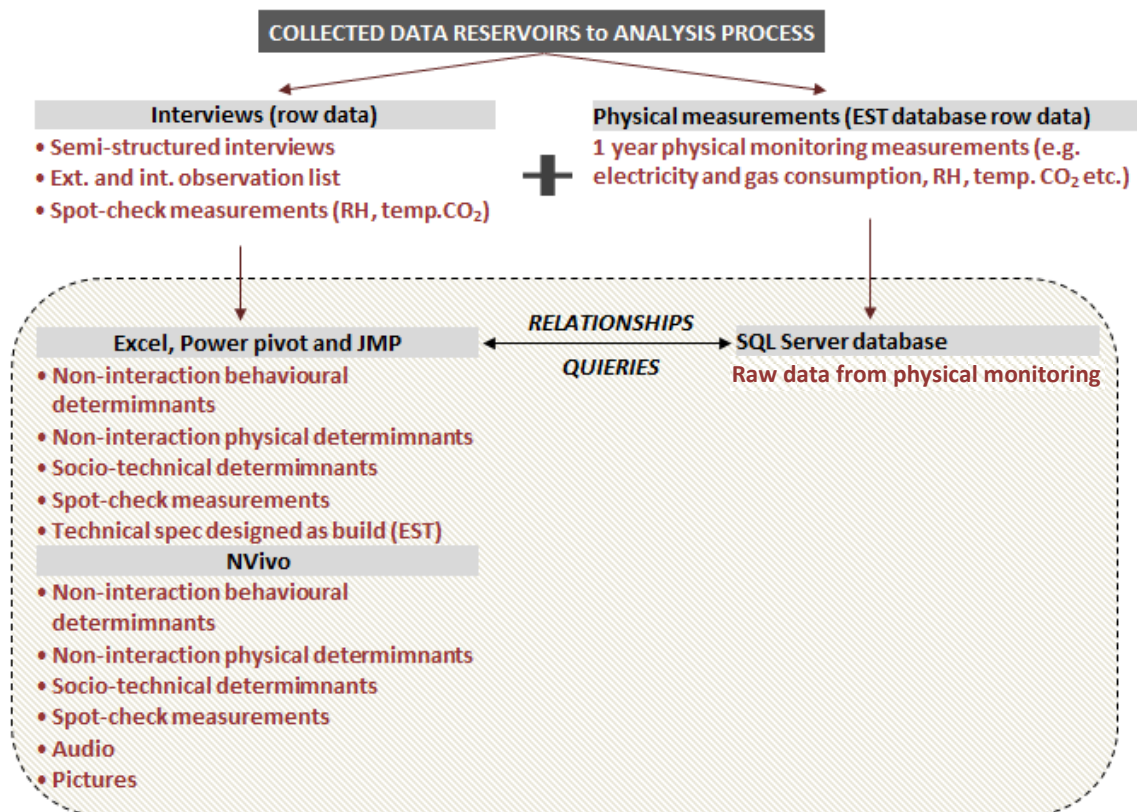


Figure 45: Data sources and tools for analysis.

Depending on the type of data input, these tools were used accordingly, employing correlation and comparative analysis techniques. These techniques were used to explore the correlations among variables (e.g. bill payment and heating controls) within the sample, followed by techniques exploring the differences between groups (e.g. occupants before and after refurbishment and level of heating controls). To interpret the strength of the correlations found in the sample (e.g. between heating patterns and occupancy), the

study takes into account previous research conducted on household energy use of larger datasets (e.g. Schipper et al., 1989, Steemers and Yun, 2009, Kelly, 2011) sets a context for interpretation of the analysis, as will be discussed further in Chapter 8 .

5.7.1 Correlation analysis

In this section correlation and regression analysis were discussed together since both, in a sense, deal with relationships between variables. Correlation analysis has allowed a better understanding of the study's data. It has also enabled determination of the extent to which changes in the value of an attribute, such as occupant health condition, are associated with the changes in another attribute such comfort and controls (see Appendix 12). The analysis has explored correlations between variables established in previous studies' findings (e.g. Schipper et al., 1989, Carlsson-Kanyama and Lindén, 2007, Steemers and Yun, 2009, Gram-Hanssen, 2010), from literature on this topic (see in Appendix 7, Table 21). However, some of the correlations from previous studies' findings related to income and type, age and size of house, number of windows, and type of equipment were not applicable for the RfF sample and not taken into account in the thesis analysis. The reason for this was that choice for the building or systems installed cannot be affected by the economic status of the social tenants in the RfF sample as this was anticipated by the housing authorities. The study has taken into consideration previous studies' correlations and those identified in the sample to develop an initial thematic map showing relationships between variables. Employing the previous interrelation analysis the causal correlations (if any), between independent and dependent variables, in the selected data sample were identified.

The analysis searched for correlations between variables within groups that either were established by previous studies or were formed by events of interaction in the sample. In the former group correlations identified from the literature (e.g. Steemers and Yun, 2009,

Schipper et al., 1989, Kelly, 2011), such as those between the type of house and number of heated rooms were further extended by looking also at correlation with heating equipment, heating controls prefiguration (active/passive measure or user), occupancy patterns and heating consumption. Within these areas, correlations between sub-groups of variables were similarly examined; such as between heating equipment and heating controls, number of heated rooms and rooms' temperature, or similarly between occupancy patterns, heating consumption and heated room temperatures. The occupancy patterns were also analysed by looking correlations between occupants' age, family composition, health conditions and level of comfort. For the latter groups, the frequency of the event (either emerging from practices like for instance of bathing or from casual events like increase temperature due to visitors) was important for further analysis of variables in the event. Thus, for example, the frequent events of opening the window when cooking or sleeping occur in the sample were examined in relation to the passive/ active ventilation system, the frequency and operation of opening windows with the indoor comfort (internal/ external temperatures, relative humidity and CO₂) in the specific rooms. The event was then examined against occupancy patterns and energy behaviour variables, such as habits and system awareness, behaviour change and so forth. The repetition of relationships between variables within the groups indicates correlations that need to be examined further in order to aggregate correlation groups that correspond to interaction patterns. Having said that, in the above examples the analytical procedures were used in order to understand the complexities and dependencies involved in occupants' interaction; hence, trying to avoid exploration of narrow sets of variables only, the study instead looks in a systematic way at combinations of subgroups of variables and explanatory variables.

The regression analysis used includes the techniques for analysing several variables focussing on the relationship between dependent variables and one or more independent

variables. Linear regression analysis was used to examine heating performance for each household, represented graphically by the correlation of the monthly sum of energy consumption and degree days. Then a comparison was made between the different fuel systems and building performance as well as the heating performance of the different heating systems installed in the sample.

It is important to highlight that neither regression nor correlation analysis techniques were used to interpret relationships, but instead to establish cause-and-effect relationships and indicate only how and to what technical and behavioural variables affect interaction events in low-carbon refurbished buildings.

5.7.2 Low-carbon interventions and interaction comparisons

As discussed in previous sections, in the preliminary analysis groups emerged from the dataset without the need for statistical analysis. Such groups included variables, for instance of buildings' indoor air quality with active ventilation systems (MVHR) versus those with only passive ventilation (natural), or were based on key socio-economic classifications such as age or income. The energy behaviour, comfort preferences and controls, awareness and satisfaction were then examined to identify similarities or differences in occupants' interaction with the measures. The groups that were identified at the outset of the search process are shown in Table 13 below.

Moreover, the analysis of the textual data using NVivo allowed techniques of cluster analysis to highlight relationships between variables by generating natural associations of households, buildings and behaviours in the sample. This is an explanatory technique that has allowed visualising patterns in the data that share similar attributes values graphically (e.g. variables correlation diagrams, Appendix 12). This is a purely conceptual method in

the group of multivariate techniques, as it can make classifications showing important similarities and differences between coded themes and variables.

Key areas	Groups	
Building:	Type, age, location level of refurbishment intervention, type of equipment (heating space/water, ventilation), type of heating/ ventilation controls (passive, active), fuel types	- Indoor air quality with active ventilation systems (MVHR) vs. only passive ventilation (natural); - Individual system performance vs. combined system performance;
		- Same occupants before and after installation works vs. new occupants after installation works;
Occupant:	Age, income, household composition, number of occupants, health status	- Allocation in the property in basis of social support vs. personal interest to RfF property;
		- Occupants relocated during refurbishment vs. non-relocated;
		- Occupancy patterns, high vs. low occupancy
		- Opinion of the property prior to installation vs. opinion after the installation (applied only to before and after occupants);
Interaction:	Training provided (type, time, person), satisfaction with the process	- Energy bill payment by occupants vs. by social authorities (e.g. benefits);
		- Active ventilation in smoke free houses vs. smoking ones;
		- Past-experience vs. post-experience with systems' controls, comfort, energy bills

Table 13: Groups formed at the outset in the preliminary research analysis.

An important factor for achieving reliable and valid comparisons was the triangulation methods used in the study limiting biases of data and methods of analysis. The main comparisons undertaken in the analysis were between:

- Actual energy consumption for gas and electricity against the estimated and TSB standards (see Table 6, p.147)
- Modelled, actual performance of a system (heating, ventilation) and level of intervention; and
- Actual performance of a system and seasonal variations.

Within the groups discussed above and sub-groups discussed in previous sections, further comparisons were made focussing on specific groups of variables related to systems controls of the low-carbon interventions and behavioural aspects of occupant interaction. Examples are heating and ventilation patterns during the heating season of similar systems and similar changes to practices in heating and ventilation.

Summary and discussion

This chapter has discussed the data collection and analysis design of an integrated interdisciplinary mixed-method approach for exploring occupants' interaction with low-carbon measures in deep refurbished houses.

The objectives of the analysis discussed have shown the links with theories in the conceptual framework and thesis research questions in interaction. The sample that the study has selected to apply the proposed interdisciplinary design was discussed, providing an understanding of the key aspects considered in design and implementation for the study's research inquiry. The pros and cons of using the Retrofit for the Future competition projects as the data sample were discussed to provide the rationale of the sample used. The association of the study with the RfF programme and the administration and roles in the data collection design explain the study's involvement in the data collection and analysis process. Physical and social characteristics of the sample, as well as design guidance and technical specifications of the RfF competition, have outlined issues of limitations and strengths, along with homogeneity and variation, in the sample. Depending on the type of data different methods and techniques were integrated into the analysis design to explore quantitative and qualitative data simultaneously in the three key areas of a building system: the technical aspects (building fabric and systems), occupant (user) and interaction (energy use and operation). The thematic analysis has provided the main themes and sub-themes, in which the building, occupant and operation related to energy use were explored. The

past and post-experience of the occupant in the pre, post-refurbishment condition of the building defined the area of analysis, which correlated socio-technical factors in occupants' interaction involving heating and ventilation energy use. An initial thematic map has shown variable possible relationships as these emerged from the literature and preliminary analysis in the study's sample. Classification techniques have allowed evaluation of the extent of socio-technical factors in interactions, indicating correlation analysis techniques to explore relationships between variables or group of variables. Comparisons and interpretation of findings were explored using the theories in the study's conceptual framework, to allow the analysis design to define empirical evidence-based indicators of interaction between occupants (households) and low-carbon measures.

Chapter 6: Data sample analysis

The first part of this chapter discusses the evaluation of data used in this study in terms of validity and reliability and issues considered in the analysis to ensure consistency in the study's findings. The main issues emerged from the data evaluation from all data sources (primary or secondary, data collected or provided) and data types (qualitative and quantitative) used in this thesis are presented. In the second part this chapter presents only one case from the sample of 26 properties as an exemplar case study of the analysis employed to investigate this study's objectives. All analysis methods and techniques were discussed in previous chapters this chapter concentrates on presenting and interpreting links between the data analysis and theory.

6.1 Validity and reliability of data

Data quality and quantity evaluation is fundamental for mitigating and reducing the threats to the validity of data and ensuring reliability of the study's findings. The study using a mixed methods approach that combines both quantitative and qualitative data evaluated data validity within the two contexts. In this respect the quantitative data instruments and measurements validity were evaluated; whereas qualitative data was assessed through the accuracy of data collection methods and triangulation of the information obtained. The key though in achieving both reliability and validity in this empirical mixed method research was the use of cross checking and triangulation approaches between the different types of data and methods used for collection and analysis. The study using a combination of methods and techniques in the data collection drawn evidence from different datasets ensuring that the findings are not falling into the weaknesses and biases that either datasets or one method alone may involve providing 'triangulation validity' (Creswell and Plan Clark, 2007). Potential threats to the data validity were addressed early in the study's collection design. For instance comfort interaction control variables collected and analysed

from physical monitoring, on-site spot measurements, semi-structured interview and demonstration.

6.1.1 Quantitative data

The quantitative involved validation of both ‘short’ and ‘long’-term physical monitoring measurements in the post-refurbishment process, including also the quantitative data from the semi-structured in-depth interviews.

a. One-off on-site monitoring metering’s analysis

There was good level of data both in quantity and quality of the spot check measurements conducted by the study only during the interview walk-through. Three different spot checks of internal CO₂, temperature and relative humidity were measured in different times (e.g. every minute) for all rooms in the house. The factors that could affect measurements validity like number of the occupants or pets present in the room during spot checks were considered from the study in the data normalization and data analysis. The quantitative data gathered from the semi-structured interviews was designed in ways that responses could be back-coded by the interviewer and also triangulated and cross checked with other data sources likes the study’s physical monitoring measurements and interview narratives.

b. Physical monitoring metering’s analysis

The data provided from the TSB/EST physical monitoring for each property was assessed in terms of quantity and quality. In this respect data validation involved contamination of data for the cases that there was:

- a. Lack of all types of data measurements required from the study for the indoor environment evaluation (e.g. CO₂, temperature and relative humidity);

- b. Lack of monitoring measurements for all rooms (e.g. living area, sleeping area);and
- c. Lack or large intervals in the monitoring of electricity and gas data;

Considering the above the account of data that the study was able to use after validation is illustrated in Figure 46 below.

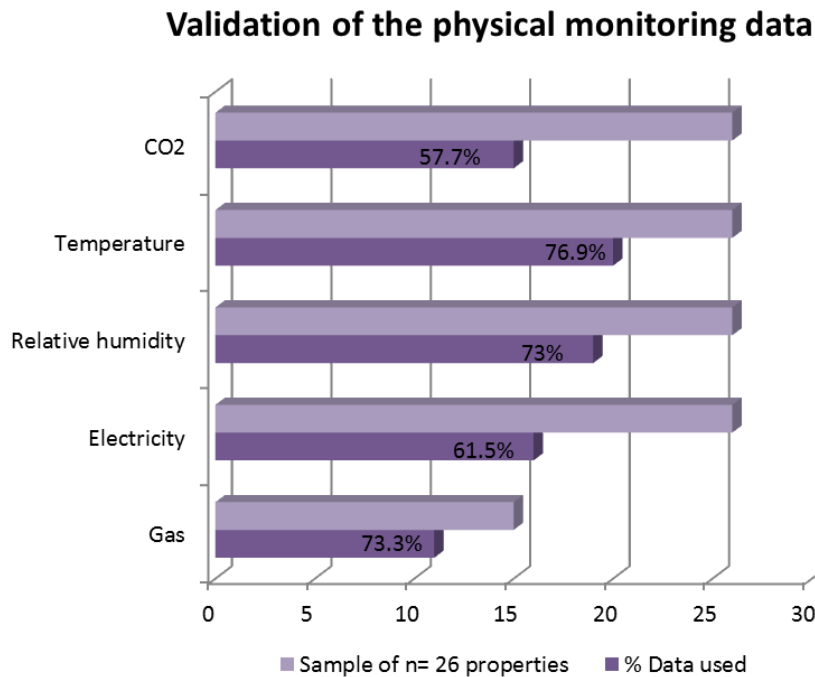


Figure 46: Percentage of the physical monitoring data provided by EST/TSB and used by the study after validation.

The data was normalized to let queries design explore research objectives in the SQL data base which involved adjustments like on the: data units e.g. pulse to kW; monitoring intervals like 1mim to 5min etc.; coding like coordination of rooms' data name. The level of the monitoring detail has also allowed excluding instant odd values like for instance like Table 14 shows. Only for a few cases (n=3 out 26) the monitoring data provided by the RfF competition was involving windows' opening/closing sensors to capture especially fundamental aspects of occupants' interaction practices in heating and ventilation.

Household Id	Data date entered	Odd values
TSB098	24/07/2012	Gas: 8063.565 kWh/day
TSB041	24/11/2011	Gas: 8618.351 kWh/day
TSB098	09/05/2011	Electricity: 21977 kWh/week
	16/05/2011	Electricity: 52401 kWh/week
TSB040	07/04/2012 01:25:00	Temperature: 91.36 °C
TSB033	11/02/2012 14:14:00	Temperature: 86.02 °C
TSB087	31/08/2010 08:58:00	Temperature: 94.29 °C

Table 14: Example of instant odd values excluded from the study's data analysis.

However the lack of consistency in data collection constrained meaningful data on windows' operation has on occupants' ventilation practices and its impact on the mechanical ventilation installed. Nonetheless, despite such limitations the study's association with the RfF completion process to a large extent has also provided credentials of validation and reliability of the data sources (e.g. measurements provided by monitoring companies) in which the study had no direct control or participated in the collection process (e.g. cases documentation, thermal imaging and air pressure tests, etc.).

6.1.2 Qualitative data

There was generally good level of qualitative data both in terms of quantity and quality. Triangulation validity approach in the qualitative data was used cross checking information from different sources e.g. transcripts, pictures, observational notes, controls demonstration and physical monitoring with occupants' 'sayings' for each household; whereas the reliability of occupants' sayings was also validated to certain degree from the other members of the household participating in the semi-structured interview. A representative sample of data from the occupant survey was also peer reviewed from experts in socio-technical research to identify whether the same or different codes and themes were assigned ensuring reliability of the research.

6.2 Case study sample analysis

The data presented in this section provides an example of analysis of one case only (TSB054) for more comprehensive understanding of the analysis of all the cases in the study's sample presented in Chapters 7 and 8. The analysis of the specific case was on the availability of detailed physical data provided by EST/TSB at early stages of this thesis and the early delivery of the project²³ that allowed the author of this study to proceed with rest of data collection process like conducting the occupant survey, spot checks, etc.. In this section the structure uses the analysis objectives discussed in Section 5.5 (**Error! Reference source not found., p.Error! Bookmark not defined.**), to explore the empirical material, focussing on the ways the low-carbon retrofitted building was designed, built and operated. Occupants' interaction with low-carbon interventions were explored in line with the study's research questions. This section begins with an extensive discussion of the building system providing all the technical information required to understand the context in which occupants' interaction occurs; next, it defines the socio-demographic and behavioural determinants involved in the household's background, comprising the household's characteristics. Once the components of the building as a system were defined, particular focus was given to the socio-technical determinants involved in interaction with low-carbon measures and practices of heating and air quality comfort. The conclusion and discussion are restricted to the findings of one sole case; some of the analytical methods that constitute thesis methodology had to be adjusted since some of the correlation and comparative analytical methods could not be applied for one case only.

²³ Due to the delays of the building teams for the rest of 25 cases in delivering the projects to the tenants there was a significant delay in monitoring data availability and for the study to collect the rest of the data required for this study's data analysis.

6.2.1 Sample analysis technical determinants

As discussed in the study's methodological approach the technical analysis provides the information related to the physical aspects of the building and of the technical determinants as these were designed and modelled by the project team.

a. Building context

The late 1800s end-terrace 2-bedroom property is located in a residential area of historical value with low rise buildings next to Oxford University residence halls. The orientation of the building (front facade facing south-east) allows solar technologies to be installed on the front roof. Surrounding buildings as well as the high trees on the north-east side of the building do not affect the performance of the solar systems proposed. The property was initially constructed as a mid-terrace, but after the demolition of the attached house has turned into an end-terrace but without any provision for improving the exposed party-wall. The two-storey property also includes a two-storey extension with facilities rooms in the back façade. The layout development is that of a typical two floor mid-terrace, with the living area on the ground floor and with bedrooms on the first floor.

b. The level of refurbishment intervention

The design strategies involve a number of low-carbon interventions to improve the poor condition of both the building fabric and systems. The condition of the building type of the property pre-refurbishment interventions has contributed to the poor indoor environment (draughts, mould/damp, variation of extreme temperatures in the rooms and floors, and poor comfort levels). Key issues related to the inadequate insulation of the fabric with significant air leakage, draughts and damp in the building were considered heavily in the proposed airtightness intervention strategy. Thermal images of the construction elements of the building fabric (Appendix 13, Figure 130, Figure 131 and Figure 132) before the

low-carbon improvements illustrate the poor condition and justify the choice of the proposed design strategies. The poor levels of natural light in the building, due to its orientation, distance from the surrounding buildings and design of the ground layout, were also issues integrated in the proposed passive design solutions.

In line with low-carbon and passive design principles, the improvements meet high AECB standards (between the Silver and Passivhaus standards). Overall the level of physical intervention in the house can be classified as in the deep refurbishment (DR) process (see Section 5.6.5.3., Table 12 p.186).

The modelling tools used were SAP 2005 for modelling primary energy use and the PHPP to verify the final package of measures. Table 15 shows, the building fabric interventions and low-carbon systems and measures undertaken to the building.

Building fabric interventions	Systems and measures installed
External walls insulated internally (or externally)	Condensing Boiler
Roof insulation	Solar Panels
Triple glazing windows (in all rooms)	MVHR system (fans in all rooms)
Concrete ground floor (vacuum insulation panels)	Solar PVs
Layout changes (living area)	Intelligent control systems (Microwatt monitoring equipment)
Draught proofing entrance area (second door)	Sun pipe light

Table 15: Building fabric interventions and systems installed.

c. Building fabric

In the ‘as designed’ state the solid brick walls of the building fabric in the main building and the cavity brick walls of the extension were insulated internally and externally to high standards. The insulation strategy also included insulation on the pitched, flat roofs as well

as the ground floor construction. Regarding the openings the windows were replaced with triple glazed systems, keeping the original size and changing the type of some of them from sash/tilt to pivot/tilt. As well as four roof lights were proposed for the rear (north-east) of the house, to improve daylight levels in the rooms. The old wooden door was replaced with a glass door of more than 60% glazing to contribute to the natural light quality, whilst a second glass door was added in the heated hallway to limit heat losses. In the design proposal the ground floor fireplace is sealed while the designed thermal bridges are modelled to accredited construction details to achieve recommended standards for the airtightness strategy.

d. Building systems

The fuel strategy is mains gas and electricity. For space heating the previous gas central heating system was replaced with a new condensing boiler and radiators with thermostatic radiator valve (TRV) in all rooms. For space heating controls both thermostat and a programmer were provided, whilst a Microwatt energy monitoring display was also considered to provide energy use information. The strategy for hot water involves solar panels on the South-east façade using the gas boiler as backup. The design also includes the installation of a 1 kWp photovoltaic array module facing south-east. For ventilation and cooling mechanical ventilation with heat recovery system was proposed for the winter (cold) months; and natural ventilation with openable windows with daytime use of MVHR and night purging during heat waves is provisioned for summer (warm) months. The mechanical ventilation with heat recovery was designed to recycle 80% of the thermal energy from the air.

e. Building performance

The energy use before and after the improvements for electricity and gas was estimated using SAP and PHPP modelling approaches in the documentation. The ‘as designed’/modelled building performance was compared against ‘actual’ in-use pre and post-refurbishment performance. The comparison shows a significant gap between the ‘actual’ values and those estimated in both the pre and post-refurbishment figures (Table 16 and Figure 47). More specifically, the difference between the ‘actual’ pre-refurbishment electricity values shows an increase compared to the estimated value of 209.35%.

		Electricity <i>(kWh/year)</i>	Gas <i>(kWh/year)</i>
Pre-refurbishment	SAP Modelled estimations	802.00	24138.00
	Consumption from ‘actual’ (bills)	2481.00	9465.16
Post-refurbishment	SAP Modelled to RfF targets²⁴	1272.40	3375.60
	Post-refurbishment (2011-12) ‘actual’ (monitoring metering)	1790.64	5526.50

Table 16: Comparison of previous, estimated/modelled and measured energy consumption²⁵.

²⁴ The predicted consumption (pre and post-refurbishment) as estimated in GUPTA, R. & CHANDIWALA, S. 2010. Understanding occupants: feedback techniques for large-scale low-carbon domestic refurbishments. *Building Research & Information*, 38, 530-548.

²⁵ The consumption figures (actual and estimated) are sourced from the TSB documentation provided by the applicants and monitoring data.

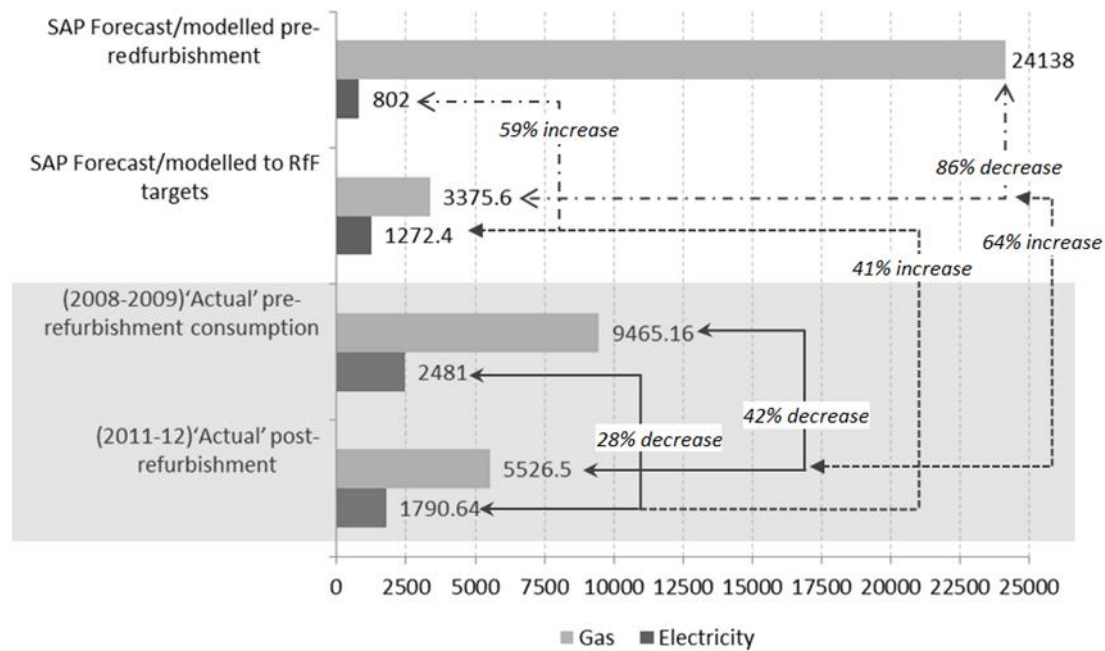


Figure 47: Gas and electricity consumption (pre and post-refurbishment) actual and estimated (in kWh).

The content of the qualitative data has provided detailed information for the analysis and triangulation. The monitoring metering from the field trial, provided by TSB in this analysis, contained data only for 6 months (year 2012 Feb.-Jul) and merely for gas and electricity. The study acquired data for 9 months (year 2011 Mar-Dec) with all metering readings included (Appendix 14: Figure 133, Figure 134 and Figure 135). The one-off on-site spot measurements were triangulated with the monitoring data. Data filtering was carried out using SQL on all numerical data excluding faulty values from monitoring equipment.

The figures for both gas and electricity indicate a failure of the SAP modelling tool to estimate accurately the performance of the building in the pre-refurbishment stage, which indicates issues of ‘prebound effect’ as discussed in Sunikka-Blank and Galvin (2012) study. Therefore, there is a substantial drop of ‘actual’ consumption between the pre and post-refurbishment values of 71.2% for gas and 38.55% for electricity. However, when

comparing the post-refurbishment values (2011²⁶) and those predicted, there is an increase of the ‘actual’ consumption in both gas (boiler use for space heating and backup for the hot water) and electricity of 63.71% and 40.72% respectively. In the predicted electricity consumption SAP assumes a 697.73 KWh/year for lighting and 574.62 for electricity requirements for pumps and fans of which 399.62KWh/year is only for the MVHR system. Such differences were evaluated in other properties as well identifying similar electricity consumption indicators for further analysis. This aims to explore issues with the ‘actual’ electricity consumption for pumps and fans focussing in particular on the MVHR system (installation and consumption ON 24/7 per year) and also on occupants’ behaviour changes that might have led to increased energy consumption. The calculation of the energy performance line for the year 2011-2012 shows that the building system in terms of the degree days does not perform as expected (Appendix 16, Figure 136) the R² value around 0.7 is likely an indication that the heating control is either very poor, or that the analysis methodology²⁷ needs to be improved, requiring more data and further analysis. Aspects from this analysis were investigated in occupants’ ‘sayings’ and with the analysis of other interaction aspects related to energy consumption.

6.2.2 Single building analysis of non-technical determinants

This section provides occupants’ background of the building ‘as occupied’ including occupancy socio-demographic factors related to interactions. The occupants of this property are a British couple (age group 50-65) that lived in the house for 21 years before the low-carbon installation works. In this case allocation factors were not related to occupants’ current health conditions. The couple’s occupational status is mixed with the

²⁶ The monitoring measurements for gas consumption available for the year 2011-2012 have not included the months of December and January. In order to allow comparisons in the study, for those months the study assumed an average value between the November and January metering readings.

²⁷ This indicates possible incorrect gas metering readings, irregular building occupancy that has not been corrected for, and heating metered together with other energy consumption that varies considerably throughout the year.

female working full time and the male not working due to health problems. Generally the house is fully occupied throughout the year (max. 4 days out of the house). On the weekdays the household is 24h occupied whilst on the weekends it is vacant only in the morning hours until 14:00 in the afternoon. The occupancy in the house is highly related to the health condition of one of the occupants. The couple spends most of their time in the open plan living room-dining room and only the sleeping hours in the upstairs bedrooms. Social roles and responsibilities along with individual factors shape the overall household's lifestyle. Another social factor related to the interaction with the measures discussed in the following sections was the role of each occupant within the household composition (e.g. couple).

a. In-use evaluation of interaction

This section examines technical and non-technical variables involved in occupants' interaction. From the observational data no major differences were found in the low-carbon interventions between the 'as designed' proposals and their 'as built' implementation. One of the minor issues was a reduction in the number of the roof lights (from four to one sun pipe in the stair landing space facing north-east where no direct natural light was available); however, this has not substantially affected the 'as built' determinants in terms of natural light quality. Another issue was the energy display equipment (Microwatt); this was related to malfunction and lack of technical support rather than to differences with the 'as designed' building system. This equipment was initially proposed to provide information to the occupants about their energy use but has never worked since it was installed.

It is also important to outline how the new layout of the house prefigures its use. In terms of layout design in the 'as built', the ground floor bathroom is designed to disability standards, whilst on the ground floor and first floor the storage space has been converted to

closets for technical equipment and tanks. The space required for technical equipment was a significant drawback in occupants' level of satisfaction; this lack led the use the study room mainly as storage. An important design change in the ground floor layout was the change in the living room and dining room from separated rooms to an open plan (with wide separation glass doors). This has not only changed the levels of natural light and heat flows but also the overall use and occupancy of the space. The occupants tend to use the open plan space more, with the separation doors always opened. The room size changed due to the internal insulation in the living; however this was not a problem for the occupants as they said 'all our furniture still fit'. There are rooms within the house with more personal or common use for each occupant. Thus the living room is the personal space of the male and in a typical day he spends more of his time there listening to music or reading (sedentary activities); the dining room has a social character and the space is arranged to serve the couple's common activities as well as the female's personal activities after work. The rest of the occupied rooms in the house are for other common activities such as cooking, sleeping, bathing, etc.

Practices of regulating the indoor climate were explored for both individuals, focussing on the ways these shaped the household's system characteristics. The study also examines the ways individual practices separately affect space heating and ventilation and the ways these two are interrelated with and affect one another. The following section describes how the space is defined by the occupants in terms of use related to their comfort levels (temperature analysis), occupancy and controls, as well as how heating and ventilation systems prefigure certain of the occupants' habits. The analysis of the occupants' 'doings' and 'sayings' was used to verify their actual awareness of heating and ventilation controls by triangulating empirical on-site observations with the physical data of nine months (March to December 2011).

b. Past-experience interaction

The couple's past-experience of the property, as expressed by them, was generally negative due to the very poor environment of draughts and cold indoor conditions, whilst their comfort was explained to be very poor and intolerable. Although they had a sufficient level of awareness of energy use and costs, and a good understanding of previous controls (i.e. related to heating to warm up by adding extra layers of clothes), the poor conditions of the building environment did not allow them to have actual control over comfort. During the refurbishment process frequent visits to the construction-site to keep updated with the works progress have raised occupants' level of awareness regarding the depth of the refurbishment intervention. This has also allowed them to have some level of design choice, especially for the facilities built for people with mobility issues. They were very enthusiastic to be part of the RfF project and generally quite supportive and satisfied with the process. The relocation during the works was generally a negative experience for them; however, this has not affected their expectations as much as the lack of communication they experienced with the project stakeholders and time lags in some refurbishment works. The main disappointment came from the lack of communication, coordination and information provided on the design interventions by the design team and local stakeholders.

c. Post-experience interaction

The post-experience living period in the property, after the installation works and up to the day of the interview, was 10 months. During this period the couple experienced both a heating and a cooling season in the property. Although they had initial concerns about the performance of the airtight property during the warm months, after they moved in their opinion has changed considerably. Overall they are satisfied with the experience living in the property after the low-carbon improvements. In terms of behaviour change, although

they were always quite environmentally conscious they believe that the refurbishment led to a significant drop in their energy bills and rising of their awareness. Generally occupants' post-installation level of energy efficient behaviour is good, with the male being particularly interested in the energy saving aspects. Of the couple the male in particular has a good level of knowledge of measures and materials with a good understanding of the retrofitting benefits. Their level of knowledge on energy efficiency issues derives mainly from their personal proactivity and interest in energy matters. The training and instructions provided, by the local authorities and the project team were insufficient overall and took place at different times after they moved back into the property. The training they received from the local authority some-time after they moved in was about basic controls for the boiler, specifically how to switch it ON/OFF and set the timer for the heating. The instructions they received from the local authorities, five months after they moved in, was limited to a booklet with very basic information on energy issues, but not on the controls of the measures installed. For the water controls from the solar panels they had a brief introduction from the project team (architect) several months after they moved in. Overall their level of satisfaction regarding the instructions and training provided is very low as they were given little information and very poor instructions for only some of the measures but not for all installations as a whole.

d. Post-experience occupants' thermal comfort adaptations

Regarding their comfort the occupants have made physiological and behavioural adaptations directly related to both heating and ventilation actions. The physiological parameter is related to the health status of the two occupants, who have different thermal comfort needs. The male particularly feels the cold, especially when under medication, while the female feels too hot due to menopause effects. Despite their comfort differences both occupants have a good understanding of their comfort level, feeling comfortable at

22°C. From the spot measurements carried out the day of the interview (9th September) the mean internal temperature on both floors was around 22°C and the external temperature at around 14°C; this temperature difference was expected for a thermally well insulated building and justifies to some extent occupants' awareness of having the heating OFF on that day.

Figure 135 (Appendix 16), illustrates the temperatures for the rooms with the highest occupancy (such as the living area on the ground floor and the upstairs master bedroom) for the month of July. It shows that despite the significant drops of the external temperatures overnight the internal conditions remain quite stable. The analysis of temperature levels for October (Appendix 16, Figure 138) allow exploration of what the occupants do and say in terms of occupancy, comfort and controls. The drop of the external temperature by the end of the month shows slight peaks of temperature in the living area and more significant ones in the bathroom (which confirms a warm environment in the bathroom in the morning). Therefore the lowest temperatures of occupied rooms are found in the main bedroom. Generally there are minor temperature fluctuations in this specific room compared to other rooms, with the temperature rising only during occupancy times (sleeping hours). Occupants' comments and on-site observations explain the temperature drop in the monitoring measurements in this room as throughout the year the window is always slightly open and the TRVs turned OFF. This temperature control mainly occurs due to the occupants' comfort preferences for sleeping in a cooler environment. The male's preference for taking hot baths in the morning hours explains the temperatures in the downstairs bathroom, which are the highest in the house, with a maximum of 25.5°C. Temperatures (23.3°C) slightly higher than what they declared to be their comfort levels are found in the living area (living room and dining room), rising

especially in the early afternoon until around 10:00 pm when occupancy and activities of both occupants are taking place in the room.

Regarding the heat loss strategy of the 'as built' environment, building fabric insulation improvements were taken to high standards (U -value, thermal bridging). As discussed in the previous chapter, although insulation factors are particularly significant, having a direct impact on the overall building's heating energy use are non-interaction components. Occupants cannot directly interact with the insulation, but their comfort control actions over systems (e.g. windows, doors, heating systems) have a direct impact on the building fabric's actual performance. Consequently, in heating energy use the occupants' interaction with the low-carbon physical elements is described by the actions taken with regard to the condensing boiler via the programmer and radiators' thermostatic valves, as well as over the openings via windows and doors, as discussed in the following section.

Heating controls and occupants' doings and sayings:

Both occupants are well aware of the heating controls from past-experiences, whereas now they find new controls easier to use compared to the previous ones. There are no different roles in heating controls between the occupants having similar levels of interaction with the measures. In terms of behavioural adaptation and controls they found it simple to set up the programmer, arranging their preferences regarding occupancy times and temperature comfort levels (18°C-22°C). Their interaction with the thermostat is less frequent as they prefer to regulate their temperature preferences from the programmer. They also have full control over radiators' TRVs and the frequency of this control is dependent on seasonal temperature regulation (turning it ON around October and OFF in late February). Generally the TRV control varies between rooms and floors in the house. The occupants tend to keep quite high temperatures in both bathrooms and lower temperatures in the living area with the TRVs set at level 3 (scale 0-5), whilst in the

bedroom and in the non-occupied room (study room) radiators are completely turned OFF. The triangulation of the physical measurements confirms occupants' statements about turning OFF the space heating around April (Appendix 14: Figure 133 and Figure 135), showing that the couple consciously regulates and operates heating system controls.

Operation of openings, although traditionally related to ventilation controls, also has a significant effect on heating comfort. The interactions identified in opening control show that occupants tend to keep the doors open in all rooms, even the one not used (study room used as storage space). From the interview and on-site walkthrough observations there was no particular frequency of interaction found in the use of doors, except the kitchen door, which is sometimes closed to avoid cooking smells being diffused in the rest of the house. However, there is a significant behavioural change in the way windows are controlled now during the cold months compared to previously. The poor condition of the building fabric and very low temperatures of the internal environment before the retrofit works did not allow the occupants to open any of the windows in the house, as "it was so cold that we couldn't actually leave any window open". But now the occupants open some of the windows routinely, even in the winter, and regulate their comfort levels by consciously leaving for instance the bedroom window slightly open all the time. The same issue was found in relation to internal door control since previously they couple kept some of the doors shut to conserve heat in the rooms.

The control of the windows involves only the opening/shutting of the units since no trickle vents were installed as in the base case. In terms of frequency of controlling the windows this varies throughout the house. Therefore when cooking or bathing occupants tend to have the windows open during or after their activities. In the bedroom, except for the occupants' habit of keeping the temperature low by having constantly the window open, their interaction is also prefigured by the design and technology of the product. In the

master bedroom, while the change of the window type from a small size tilt pane to a pivot/tilt one has increased the levels of natural light and airtightness, it has also increased difficulty of operation (Figure 48 and Figure 49). The occupants cannot have full operation of the window and tend to keep the window only at a tilt. This is due to its increased weight (one pane is triple glazed) and also because of the low sill plate, which creates safety issues of falling out when they try to fully pivot the pane.



Figure 48: Base case double glazed window, tilt opening type with trickle vent.



Figure 49: 'as built' triple glazed window, pivot/tilt opening type.

Heating control using TRVs and the programmer is not 'scripted' by the technology and is left entirely to occupants to prefigure and manage interaction according their comfort preferences. As concerns windows and heating controls, openings' design in the front façade (bedroom and living room) affects operation to some extent; however, interaction is generally also affected by other aspects related to ventilation prefiguration and occupants' behaviour. Overall none of these controls had a major negative impact on occupant's interaction with heating system; occupants' past-experience made them conscious of adding an extra layer of clothes when it is required instead of turning up the heating.

Air quality comfort conditions:

The air quality of the indoor environment is provided through the passive ventilation by opening doors and windows and by active ventilation via MVHR installed in all rooms. The MVHR was designed to supply air to the long occupation rooms like living room, dining room and bedroom, and exhaust the air from the wet rooms like the kitchen and bathrooms. The interaction with the windows is directly linked with the MVHR operation, and is determined by occupants' physiological comfort, behavioural adaptation and activities in the room to regulate the indoor environment.

The empirical data was cross-checked with the physical measurements to explain the impact of the system on an occupant's comfort level related to heating, air quality and noise. The CO₂ levels measured²⁸ in all the actively occupied rooms for the nine months of occupancy indicated the levels of air quality and efficiency of the ventilation system. Thus, the CO₂ levels compared to the CIBSE indicators for adequate air quality (see, Section 5.6.5.2, Table 11, p. 184) are normal for the open plan dining room and living room but above the limit in the kitchen and main bedroom (Table 17).

²⁸ CO₂ measurements: these include the monitoring CO₂ values for the 10 months triangulated with the on site values collected on the day of the interview for all of the occupied rooms.

On-site measurements (09 Sept 2012 17:00pm)	Ground floor			1 st Floor
	<i>Living room</i>	<i>Dining room</i>	<i>Kitchen</i>	<i>Main bedroom</i>
Air Temperature (°C)	21.3	22	23	21.8
Relative Humidity (%)	56.6	55.1	57.6	55.7
CO ₂ (ppm)*	884 (normal)	998 (normal)	1414 (poor)	1136 (poor)
Apparent Temperatures for values of room Temp. and RH ²⁹	21	22	23.7	21.9

*The values recorded when there were no occupants in the room

Table 17: Indicative average values of temperature, RH and CO₂ levels in the different rooms

However, the temperature and CO₂ levels was found to be especially high in the main bedroom considering that the window remains always open throughout the day and the MVHR is constantly ON. The relative humidity levels compared to the BSI 2002 indicators are at good levels in all rooms. The relationship between relative humidity and temperatures is satisfactory in all rooms with average apparent temperatures of around 22°C, which may explain occupants' satisfaction with the indoor environment feeling comfortable at around 22°C according to their statements.

As regards the impact of the MVHR system on the overall indoor environment there is a rather even distribution of air, whilst no particular issues were identified regarding maintaining the comfort conditions throughout the house. However, the booster fans in the wet rooms (kitchen and bathroom) were found insufficient to take all the steam and humid air out from bathing and cooking practices. As a result, and despite the MVHR prefiguration, opening windows even in the cold months has been a quite common event of interaction for both occupants. They had also experienced serious noise issues from the MVHR system after they moved in, with a quite loud noise coming out of the fans that

²⁹ The calculation of the apparent temperatures for values of room temperature and relative humidity was based on the National Oceanic and Atmospheric Administration, environmental data and Information Service and national Climatic (Source: www.ncdc.noaa.gov/societal-impacts/apparent-temp/) and apparent temperature calculator tool (source: <https://www.easycalculation.com/physics/classical-physics/apparent-temperature-calculator.php>).

varied depending on the outdoor wind velocity. The MVHR system was adjusted a few weeks later by the contractors as it was aggravating the female's hearing problem. Their initial experience with the system and noise is now attenuated by behavioural adaptation with the female saying "now, I get used to it". Despite the negative aspects in their early experience with the system their comfort in terms of air quality was described as "it feels much nicer somehow much cleaner...it's difficult to explain ...it is just different".

Occupants' ventilation controls:

As seen in the previous section occupants have full control over the passive ventilation measures by opening and shutting windows and doors according to their comfort preferences. Except for the design issues identified in the front façade windows there are no aspects preventing occupants' interaction with openings. As regards the active ventilation the MVHR system is always ON throughout the year. The couple has no control over MVHR as the control is prefigured in all rooms except the bathrooms, where a boost control button is provided. The instructions they received from the project team were "don't need to touch it", preventing occupants from having any type of control over the fans or over the sole ON/OFF button located in the loft. When an equipment box from the MVHR system was literally fired up, the lack of control provided to occupants made it impossible to control the incident, as it was physically difficult for the couple to reach the ON/OFF button in the loft. Any interaction needed at the time with the system was restricted and 'scripted' by the installation design. Occupants' interactive adaptive behaviour to such an event compelled them to take control of the system by switching it OFF from the house fuse box.

In the open living space the couple is using the CO₂ level readings from the Watchdog monitoring system³⁰ to control the air quality of the room. The Watchdog display had become a control indicator for the man, in particular for opening the windows. Thus in cold months in this room only when the indication shows ‘poor’ CO₂ levels the occupants open the windows to circulate the air. This empirical means of interaction control, as Table 17 shows, brings sufficient levels of air quality into the open living area whereas the measurements in the rest of the rooms indicate that there is inefficient interaction between passive measures and active occupants’ controls. For the warmer months most of the windows tend to be opened, which leads to humidity increase and a fall in the CO₂ levels (Appendix 16: Figure 140 and Figure 142). In October the levels of relative humidity in main bedroom and living area have a similar performance, and the higher levels of CO₂ in the living area have confirmed occupants’ statements about occupancy schedule and the slightly opened window (Appendix 16: Figure 141 and Figure 143). Generally from their doings and sayings occupants seem to have a confused understanding of the new system ventilation controls; moreover, the lack of information left it unclear to them how the efficiency of the MVHR system is affected when the windows are opened in cold months and in warm months respectively.

Hot water heating and occupants’ practices:

The hot water system comprises solar panels using the condensing boiler as backup. Although occupants have a good understanding of the purpose of the solar panels as a passive measure, they have no control over it or a display to inform them of how much hot water the system generates. Apart from the boiler controls via the programmer all other hot water system controls are prefigured (‘scripted’), significantly affecting occupants’ bathing practices. The insufficient amount of hot water provided by the solar panels constrains

³⁰ The Watchdog monitoring system was provided in the property by Oxford Brookes University for research purposes.

occupants every three days (both in winter and summer) as they have to top up the hot water tank by the boiler. Their perception concerning their usage and control actions over the system is that they manage the solar panels in a quite efficient combination with the boiler. In terms of hot water preferences in the case of the ground floor bathroom, mainly used by the male, he likes using very hot water in the morning, which is sufficiently provided by the combined system. However, in the upstairs bathroom the temperature of the water is far too low and the female when bathing needs to adjust the water temperature by taking hot water from the hand basin and pouring it into the bath. This implies the failure of the domestic hot water (DHW) system pump to provide at a sufficient temperature hot water in the first floor affecting significantly occupant's bathing routines. Despite their efforts contacting different type of technical support several times to solve this malfunction the system, as of the day of the interview the system still was not working properly. This technical problem and lack of information, support and maintenance provided for the system had forced the female to alter her bathing practices, adopting indirect interaction over the DHW system to meet her hot water preferences. In this case, the installation of combined systems and the prefigured controls rendered occupants' actions harder and longer compared to previous experiences with simpler systems.

6.2.3 Discussion of the sample analysis empirical findings

The main points from the empirical findings involved in occupants' interaction are discussed under the lens of the theories that comprise the study's conceptual framework. Following the principles of the user-centred theory, occupants' experience (past and post) has been described in terms of the interactive effects between occupants and the building environment. Particular events of interaction were highlighted by adaptive theoretical approaches focussing on the behavioural, physiological and psychological factors that influence occupants' everyday practices of regulating heating and ventilation. The

technology of the building environment and systems installed has shown the extent to which interaction was prefigured (or not) in the design and installation or it has been re-prefigured (or re-defined) by occupants' operation. Elements and relationships identified by these theories were connected by the concepts of practice theory (technologies, habits/know-how, engagements and knowledge), showing how practices in the new low-carbon environment hold together.

Occupants' past-experience of poor indoor environment and systems had significantly affected their comfort levels, understanding of heating controls and awareness in terms of energy cost. In the pre-refurbished environment occupants' approaches to physiological and behaviour adaptation were unbalanced. While their actions in responding to the building environment were to improve its performance by carrying out minor physical interventions to the building fabric, their comfort controls were still restricted by financial factors and the building itself. Although the building may be considered a system that allows occupants' interaction with it, in practice the physical conditions have made occupants passive recipients with merely a few controls. Therefore, interactive effects at the pre-refurbishment stage were largely scripted by the technology and products, as they were directly prefigured by the physical condition of the building fabric and systems' age and type. Concerning how the heating system and fabric influenced occupants' practices, at this pre-refurbishment stage, this was more strongly related to their habits of operating heating controls and openings. Hence, there was a practical understanding and know-how relating to choosing their habits consciously, for instance to not open the windows and keep all the doors closed during cold months to prevent heat losses. Occupants' financial interest in saving energy and maintaining sufficient comfort levels provided the meanings and engagements that in the pre-refurbishment stage affected practices relating to the heating and indoor climate. These aspects as theoretically related to practice theory

elements are described as embodied habits, know-how and engagement. However, for some of these aspects there was a significant behaviour change affecting some practices in the post-refurbishment stage.

There is an intermediate stage between pre and post-refurbishment works in which occupants' perceptions and engagement with the refurbishment process were affected in both positive and negative ways. Their engagement with the project gave them the possibility to meet the project team and allow them to affect to some extent the design process of the building environment based on their needs (disability standards in the ground floor bathroom). At the same time it allowed them to have a clearer understanding of the scale of the low-carbon intervention. Their engagement at this stage could have been a good starting point for the couple to receive better information and support for the new measures from the team of professionals, but ultimately has not turned out this way. This is mainly because the level of engagement of the project team and local authorities' stakeholders in providing information and transferring knowledge had failed in terms of time and communication means. In this case the type of knowledge is different to what practice theory relates to describe institutionalised knowledge and explicit rules about indoor climate and comfort controls. Occupants' knowledge refers more to the general information they have received over the years from television, newspapers and the web, and is mostly gained from their own proactivity to learn about environmental issues related to materials, heating and energy consumption.

In terms of overall satisfaction the couple was generally positive about the post-experience in the refurbished building environment. There is a significant behaviour change in interactive effects determined by both how occupants were affected and how they were reacting to the refurbished environment. In their control related behaviour in regard to heating comfort, the main change in their habits is in operating windows and doors. And

the know-how of regulating the radiator valves involves a transfer of knowledge from past-experiences of interaction with the technology. The airtight building environment and the ease in controlling the heating system allow the couple to choose their habits and adapt their routines in a more impulsive way. Thus in the post-refurbishment environment occupants are active users dealing with an active heating system that responds to their controls and supports their physiological and behavioural preferences. Despite the design aspects affecting window operation there is a significant behavioural change in the female's perceived need to keep the bedroom window tilt all the time regardless of the temperature outside; this is not only a physiological effect (menopause, asthma health condition) but as she explains also a cultural issue: "...it's how I grow up". In this case how the individual explains her cultural values and routinised habits by trying to associate them with other conditions and rationalise them to herself is relevant. Concerning passive ventilation, although the technology in the wet rooms was prefigured, involving active user interaction with the boost button, in practice the regularity of opening the windows was an added element in the interaction that moved beyond the script. The system in the rest of the rooms was refigured for passive users and scripted to prevent any direct interaction with it; however, again indirect interaction occurs. The information from the monitoring display (Watchdog) in the living room has stimulated occupants' indirect interaction with MVHR, affecting relevant practices in ventilation of the specific room. In the living area the occupants' technical interest and their 'energy satisfaction' in of 'doing the right thing'³¹ technically contrasts with their ventilation actions in the rest of the rooms (e.g. bedroom window open) varying in CO₂ levels concentration (Table 17, p. 215). This highlights that although occupants can be engaged in regulating indoor air quality the meaning of the

³¹ The 'right thing' for the occupants was to open the windows any time the indication on the display (Watchdog) showed poor levels.

things they do is different from the knowledge and technical understanding they have in relation to complex systems (heating vs. ventilation, active vs. passive use).

Behavioural and psychological adaptation related to the occupants' habits, comfort and expectations were also related to the ways thermal perceptions and practices of bathing were altered after the low-carbon installation. Although the combined hot water system was designed as an active system in terms of controls, its installation dictated passive users to some extent. Eventually the lack of systematic information, instruction and support provided for the systems installed resulted in occupants having a mixed understanding of which practices and measures affect each other. Compared to the base case the considerable reduction of their bills was the only instrument of knowledge providing feedback to occupants' environmental, technical and economic awareness and constitutes a practical representation of their behaviour with the low-carbon measures.

Summary and conclusions

Drawing on the analysis and discussion above it's clear that occupants' interaction was influenced by the low-carbon measures and retrofitted building environment in which it occurs, but it was not determined by it. The main interactions between the low-carbon measures and occupants were found in the couple's practices to regulate thermal and air quality comfort. The interactions associated with the control of the indoor temperature were mostly engaged with practices of sleeping, cooking, bathing, relaxation and entertainment. Concerning the frequency of occupants' interactions, to a large extent these have occurred with routinised regularity and often with seasonal dependency. The analysis has shown that active measures 'as designed' and installed have fostered direct interaction involving active users; whilst the passive low-carbon measures were designed and installed for passive users they tend to involve indirect interactions with active users.

The couple's knowledge transfer from previous heating comfort practices and controls has been compromised to some extent by the post-experience of living in a satisfactory indoor environment overwhelmed by 'forgiveness' and 'forget' factors (Cohen and Bordass, 2015). Occupants' personal interest and proactivity were important to hold practices together. However, there was a lack of systematic training and information on how various practices in integrated combined systems can inefficiently affect one another. This has apparently had an influence on household interactions. Therefore, although gas consumption has improved significantly compared to the base case it is still higher than predicted, whereas in the actual electricity use, the additional installed pump and fan equipment (e.g. PV panels and MVHR ventilation system) had increased consumption more than predicted. The lack of controls on the MVHR as well as installation factors needs to be examined and compared with similar cases. The factors affecting the gap between predicted and actual case were taken into consideration for further analysis and comparisons against the other cases in the sample.

The case study showed that despite the high occupancy in the household related to occupants' health conditions, heating interaction and controls are maintained to good levels. In heating occupants are active both directly and indirectly in positive and negative ways with heating controls. However, in the combined system of heating hot water users have a negative interaction and a passive behaviour (adaptivity) from an 'as designed' active measure. In passive ventilation occupants have full control and active interaction through openings, although not with a positive effect on the mechanical ventilation system. The active ventilation was installed and explained to the occupants as a passive measure; however, occupants have an indirect influence over it as active users by interacting with openings (windows and doors).

The findings discussed in this example are for one case only and need to be treated as indicators of interaction, considering that no correlations and comparisons between groups of variables are achievable.

Chapter 7: Non-interaction drivers in energy use

The analysis of the 26 RfF cases is presented across two chapters, Chapter 7 that discusses the factors that are not affecting directly users' interaction and Chapter 8 presenting the drivers of interaction. The structure here follows the analysis objectives as discussed in previous chapters (Chapter 5) and demonstrated in the exemplar case study (Chapter 6). The discussion puts forward the broad level of technical and non-technical analysis of determinants, which are related to the pre and post-refurbishment, and correlated indirectly with occupants' interaction. The discussion presents the factors, as found in the sample, that are determined by buildings' and households' characteristics that have no direct interaction with the users, but provide the technical (physical) and non-technical context in which interaction is taking place. This chapter discusses the non-interaction drivers involved building's characteristics including the building context and level of low-carbon intervention undertaken to the building fabric evaluated by thermal imaging and airtightness tests; whereas the low-carbon systems and measures installed in heating and ventilation viewed under the lens of their 'scripted'/prefigured (or not) attributes. The non-technical characteristics discuss the socio-economic, micro-factors, occupancy background and post-occupancy patterns of the household system. All the aspects discussed in this chapter offer an introduction to the interrelated factors examined in the core analysis in Chapter 8 where the main findings on the interaction are summarized.

7.1 Building system characteristics

Buildings characteristics involve the physical determinants and factors that have zero to low direct or indirect interaction with the occupant (user). Thus, the building context, technical attributes of the building fabric and specifications of the low-carbon measures installed in the RfF properties are included in this section's analysis.

7.1.1 Building context

Location is one of the factors related to the building's context; the focus here is on the effect it has on low-carbon refurbishment interventions. The analysis of this factor together with the climatic determinants of buildings' orientation looks at the effect they have on the design choice and installation of low-carbon measures, such as solar and ventilation technologies and wall insulation type.

Four types of properties' location emerged from the sample, with the majority of the properties be in suburban (n=10) and urban (n=7) residential areas with low rise housing. Only a few cases (n=3) are located within dense urban environments and a small number of properties (6 of 26) in rural residential areas. In cases of suburban and dense urban environments location is followed by listed buildings' limitations due to area's historical value (n=4, TSB040, 098, 054, and 034). Focussing on the effect that location has on the design choice and installation of low-carbon measures, it was found that the installation of solar technology for only one of the four properties (n=4, TSB040, 098, 054, and 034) has been constrained by conservation restrictions of the area and the building's historical value (Figure 50). However, for all four properties such restrictions had also an impact on the choice of the wall insulation and the type of installation (e.g. internal or partly internal on building's old shell and external on new rear extensions).

The natural environment in other two cases (TSB068, 069) in rural locations has significantly determined the choice of solar measures given that the houses are located in the middle of a valley and the height of the surrounding trees would have compromised the performance of the solar technology. However, this is not the case for the rest of the properties in the sample (n=5, TSB068, 069, 097, 034, 072), in which other factors not related to the building context (e.g. project budget) have determined the design choice for solar technology.

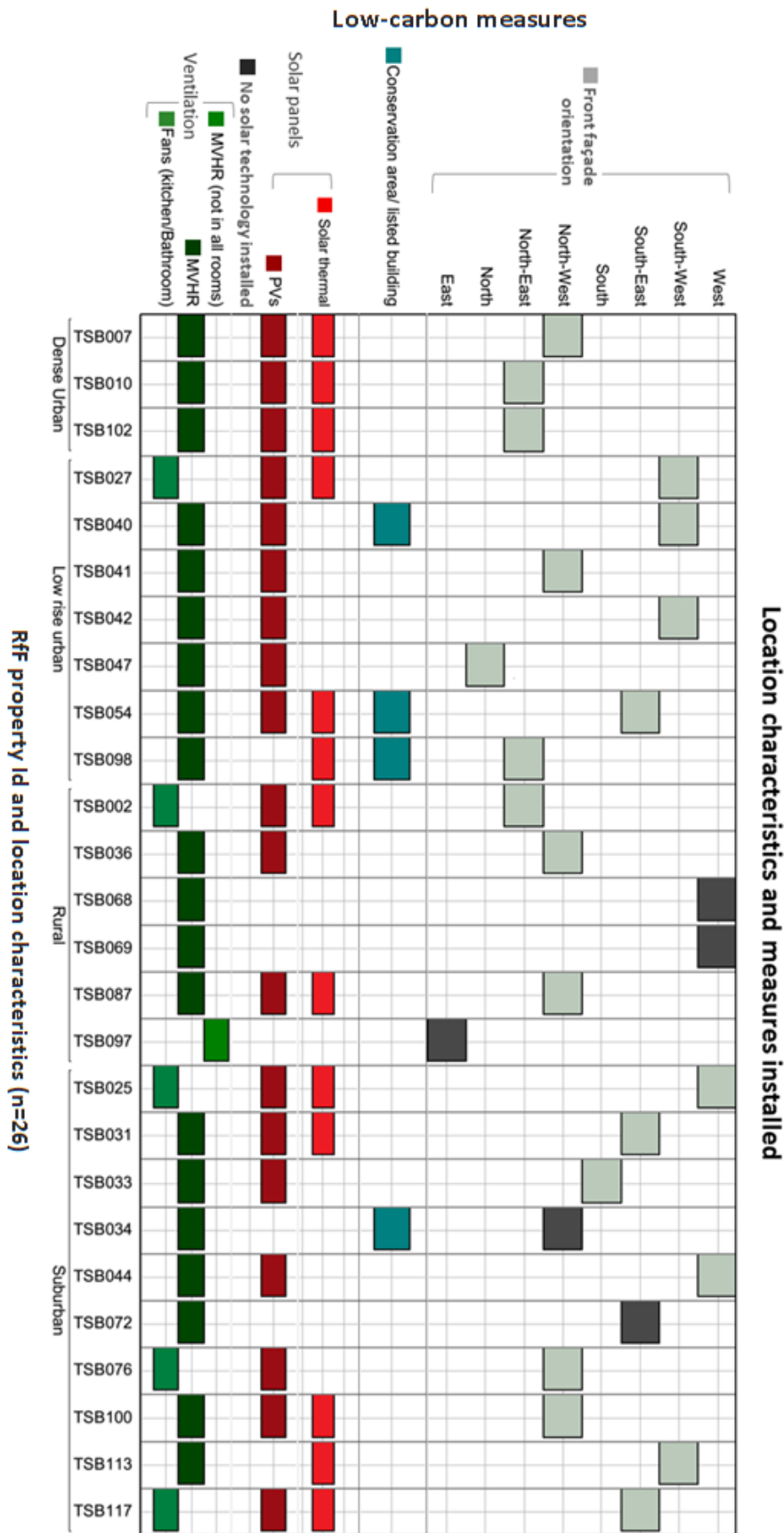


Figure 50: Location characteristics of the RfF sample (n=26) and measures installed.

The choice of installing mechanical ventilation in most of the properties in dense and in low rise urban areas (e.g. London), as shown in Figure 50, was largely led by security factors involved with window opening practices. While the combination of mechanical exhaust ventilation (MEV) measures and natural ventilation was the design choice only in a few cases in the sample. Therefore, in the majority of cases, even in rural and suburban areas, MVHR systems were installed.

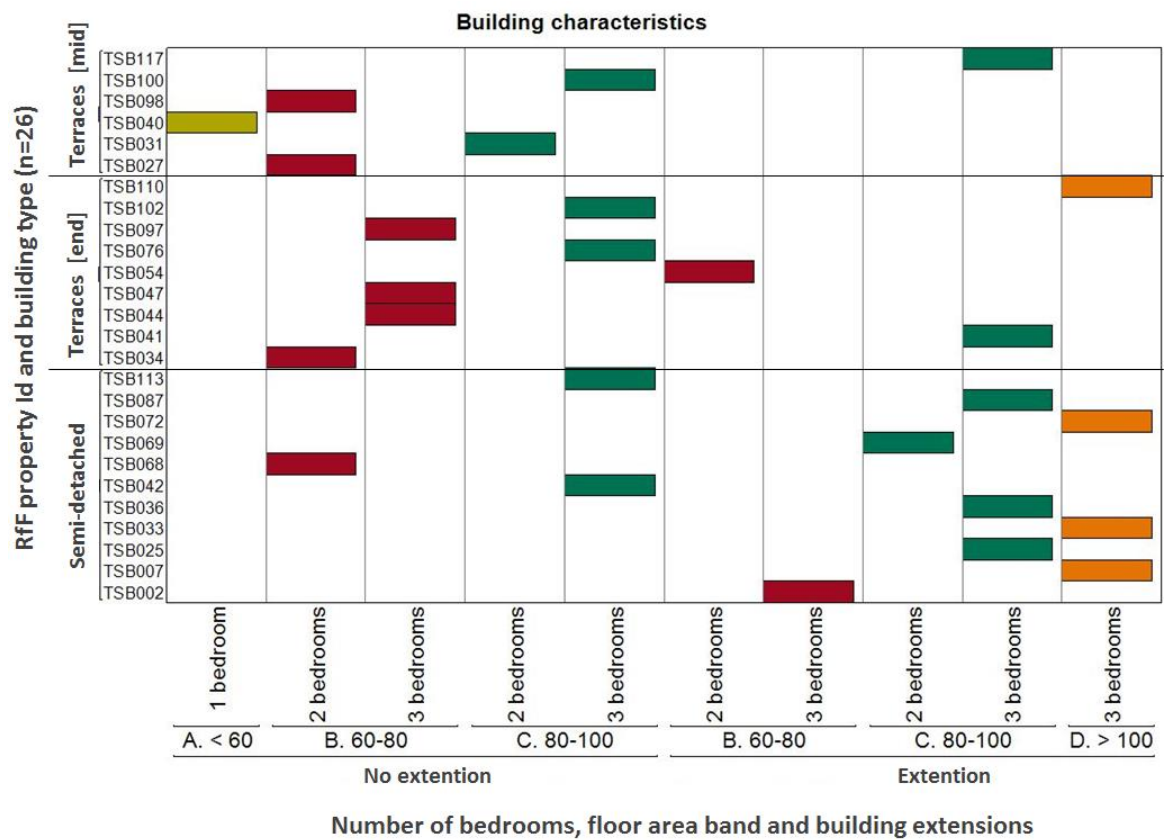


Figure 51: Building characteristics of the RfF sample (n=26).

Another physical characteristic is the building type. There are three building types that the study has considered for analysis: the semi-detached, the end and mid-terraces buildings. Most of the properties in the sample (n=11) are semi-detached and end-terrace (n=9), whereas only in six are mid-terraces (Figure 51). Except for two properties, one of a single storey only (TSB040) and another of three storeys (TSB031), all are two storey properties (n=24). In eleven cases the refurbishment intervention has also involved space extension

of the building fabric, including in most cases additional bedrooms, utility rooms and extended living space; in a few cases (n=4, TSB033,87,110,72) this involved a porch at the front entrance. These non-interactive technical factors such as the building type, size and layout extensions are discussed in the following sections in relation to the refurbishment intervention, building performance and users' occupancy in the building space.

In the RfF properties another factor among a building's characteristics related to heating energy use and a household's occupancy is the number of heated rooms. The number of bedrooms used in the UK to define the size of the house is not an indicator of the number of heated rooms in the property, as shown in Figure 52, and not always proportional to the floor area (Figure 51).

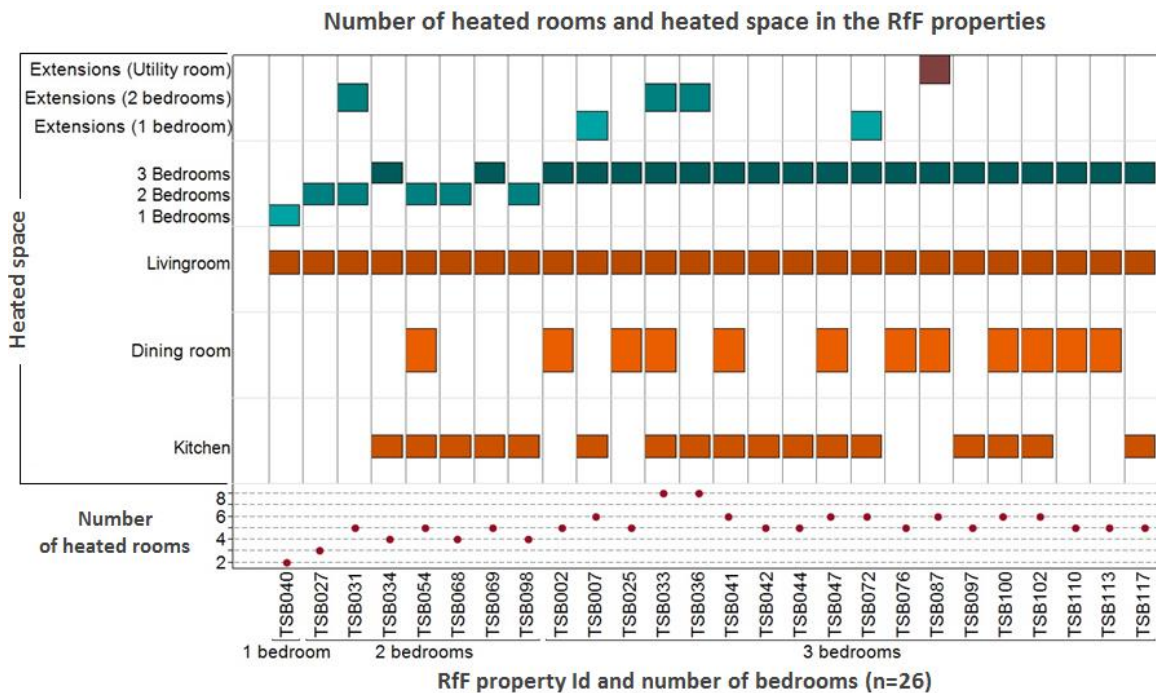


Figure 52: Number of bedrooms and heated rooms per household (n=26 properties).

The number of heated rooms ranges from four to six for the majority of the properties (n=22). There are only a few properties with a higher number of heated rooms (n=2 with 8 rooms) or the fewer number of two to three heated rooms per property. Living room and bedroom spaces are found from the on-site visit and room temperature monitoring data to

be heated in all properties in the sample. Of the fourteen properties with dining room space only two are not heated and this is because they are heated indirectly, either by the open plan kitchen or by the living room. Also, the kitchen space in three out of nine cases is not always heated at all, whereas the rest of the cases have an open plan kitchen space heated by the dining room. There is also one case (TSB087) in which the extended space for the utility room is heated and used as a study. From the above it appears that the number of heated bedrooms is proportional to the floor area of the property, hence as the floor area increases so does the number of the heated rooms. Although these are not included in Figure 52, wet rooms such as bathrooms and WCs are heated in all cases.

This characteristic of heated rooms is analysed in the following chapter in relation to occupants' interactive drivers – specifically, how they occupy space and interact with space heating to satisfy their comfort levels.

7.1.2 The level of refurbishment intervention

The refurbishment interventions undertaken in all properties in the sample were examined and evaluated according to the classification table as discussed in Chapter 5 (Table 12). Figure 53 shows the level of the overall refurbishment intervention according to the low-carbon improvements undertaken in the 26 properties. In most of the properties (n=19) deep refurbishment interventions were carried out complying to AECB Silver and Passivhaus standards (AECB, 2007) and following BREEAM Ecohomes XB methods (Topouzi, 2013).

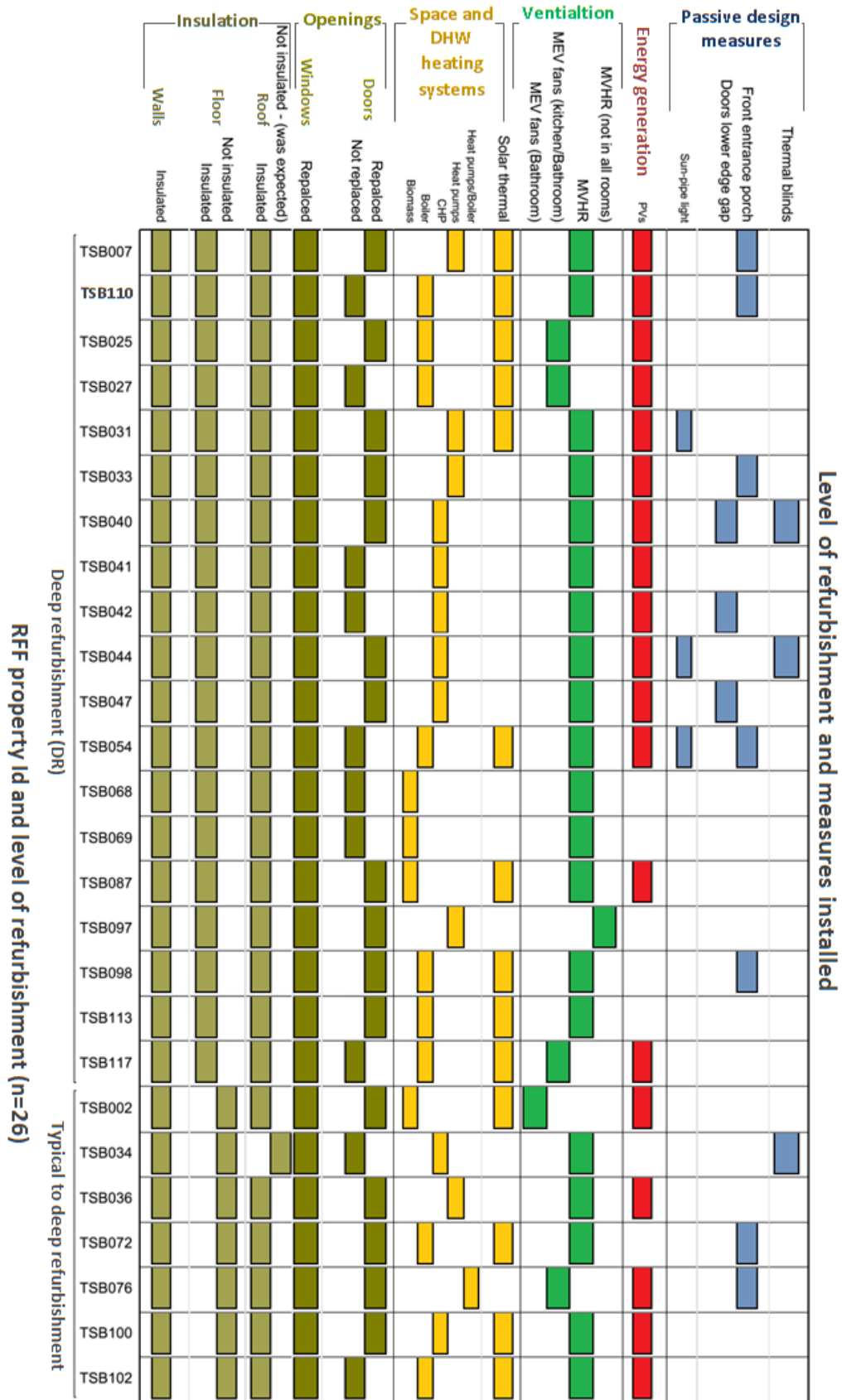


Figure 53: Low-carbon improvements and the level of refurbishment intervention in the RfF properties (n=26).

There are also properties (n=7) in which the level of refurbishment is between typical and deep refurbishment. The reason for this is that floor insulation strategies or door opening replacements were not considered in the intervention strategy of the design team. In all properties wall and roof insulation was, however, installed and windows were replaced to high specifications. Interventions like thermal blinds, sun pipe lights, front entrance porches and doors' lower edge gaps comprise the range of passive measures undertaken in sixteen properties. Photovoltaics for onsite energy generation were installed in nineteen properties. The systems for space and water heating vary from heat pumps, combined heat and power (CHP), and biomass to A+³² rated gas boilers, whereas the ventilation and cooling systems include MVHR and MEV solutions with natural ventilation.

An extensive discussion of the low-carbon improvements of the building fabric performance in terms of the airtightness strategies undertaken are discussed in the following sections.

7.1.3 Buildings' fabric

The elements of the building fabric interventions were classified by the study as non-interaction technical factors given that their technical specifications and properties have no effect on occupants' direct use of energy. There are five building construction types in the sample that vary within the three different building types (semi-detached, end and mid terraces), as shows Figure 54 below. Half of the cases have masonry cavity (n= 13) and the rest varying between solid brick (n=5), concrete frame (n=4) and mixed constructions (n= 3) such as masonry cavity and solid brick. While only one case is made of steel frame. External insulation was installed in most of the semi-detached (n=9) and end-terrace cases

³² Boilers' rating system is based on Sedbuk (Seasonal Efficiency of Domestic Boilers) in the UK. This is a system that classifies and compares boilers on their efficiency to convert fuel into heat. The rating scale is from A to G, with A being the best and most efficient (90% and above efficiency) and G the lower below 70% efficiency.

(n=4) regardless the different types of wall construction; whereas internal insulation installed only in one end-terrace property with masonry cavity. Mixed insulation has been installed in five properties with combinations of internal, external or cavity filled insulation in different parts of the building. Similarly almost in all semi-detached (n=3) and end-terrace (n=1) properties with concrete frame external insulation was installed except one with mixed insulation. In the end-terrace (n=3) and semi-detached (n=1) properties with mixed construction the choice of wall insulation solution varies based on the design strategy to achieve RfF building performance standards, like for instance cavity wall insulation and internal on the solid brick walls of the building. In three of five end and mid-terrace properties (n=3, TSB034, 040,098) with solid brick wall insulation was installed internally due to the conservation restrictions of the buildings or area; whereas the rest two end-terraces were insulated externally. Regardless of the building's construction type external insulation was found to be the most common approach in the semi-detached and end-terrace (n=14) properties in the sample, whereas the building and conservation of end-terraces as expected have narrowed insulation choices to internal and mixed solutions.

In seven out of 26 cases, of which in the majority wall construction was masonry cavity, wall insulation was to achieve a U -value³³ above 0.2 W/m^2 fluctuating between Building regulations and Passivhaus standards (as discussed in Table 2, p.61). In one of these cases with solid brick construction type it was even considerably higher above 0.3 W/m^2 . In the rest of the cases, with the majority of them been insulated externally and different wall construction types, the insulation was to achieve a U -value equal or below 0.15 W/m^2 following Passivhaus standards.

³³ The U -values of the elements of a building's fabric are used to measure how effective these are as insulators. The lower the U -value of an element is the more slowly heat transmits through it, and so performs better as an insulator.

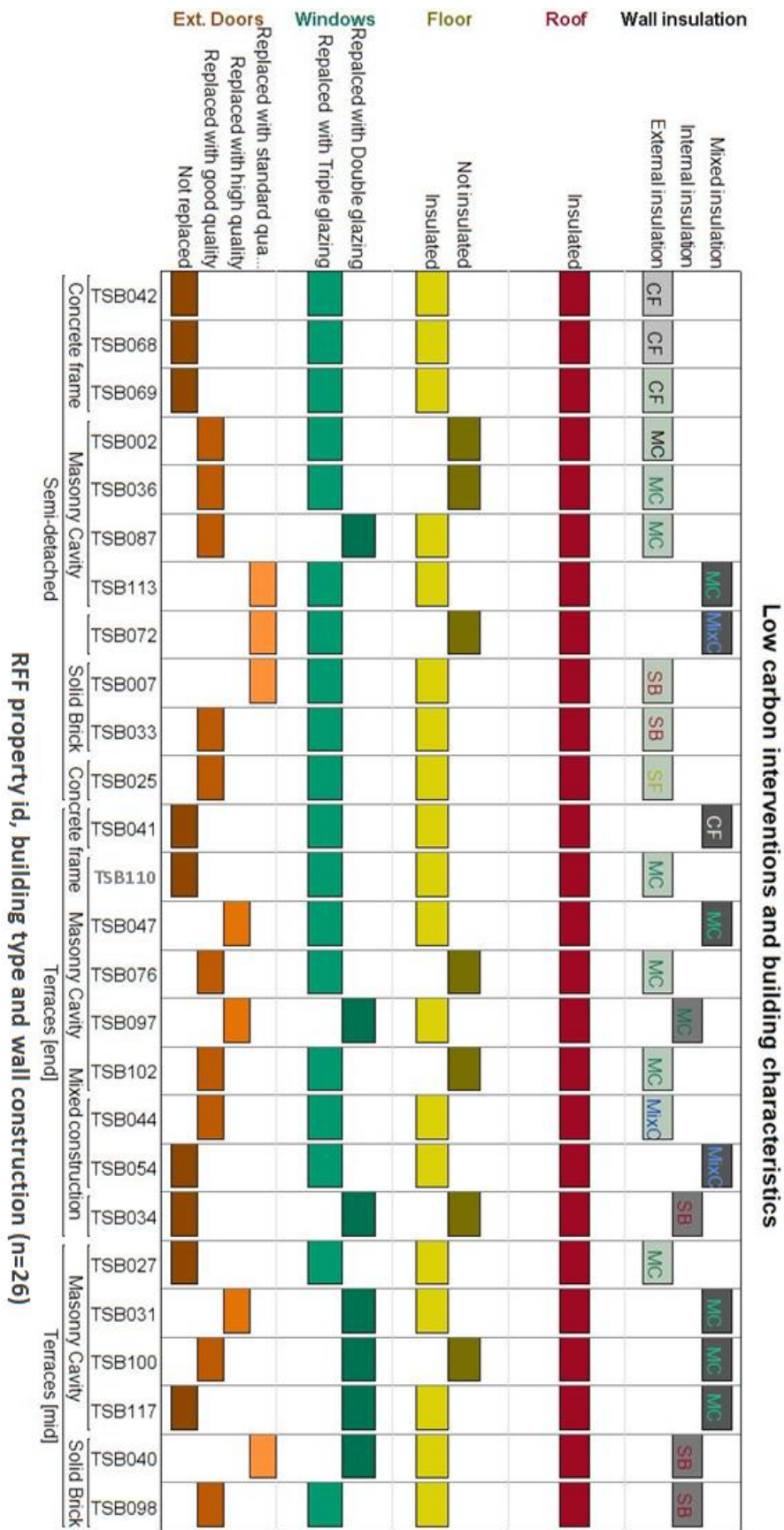


Figure 54: Properties' (n=26) technical characteristics and low-carbon interventions wall construction type, wall, roof, floor insulation and opening type.

As for other insulation measures roof insulation was installed in all properties³⁴ to achieve a U -value of $0.1\text{W}/\text{m}^2$ following Passivhaus standards; whereas floor insulation was not undertaken in all cases. Therefore in seven properties floor insulation was not installed, whereas in eighteen properties only the ground floor area or specific rooms on this floor level were insulated (e.g. living room, room extensions, etc.) in the sample ($n=26$). The suspended floor of the first level was not insulated in any of the cases in the sample.

As regards the openings, the majority of the properties ($n=19$) had the old windows replaced with triple glazing systems following the Passivhaus standards, whereas in the rest of the cases ($n=7$) high quality performance double glazing systems were installed. In the majority of these cases windows U -value was to Passivhaus standards below $0.8\text{W}/\text{m}^2$. Only in seven cases windows were to give a U -value between Building regulations and Passivhaus standards above $1.1\text{W}/\text{m}^2$. The external doors have not always followed windows' standards in the sample ($n=26$); therefore in nine properties the old door system has not been replaced. In four properties the external doors have been replaced with ones of standard commercial quality and only in half of all properties was the quality of good ($n=10$) to high ($n=3$) standards following windows' specifications.

The post-refurbishment evaluation of the building fabric with thermal bridges and airtight strategies involved thermal imaging and airtightness tests. This has allowed possible insulation defects and air leaks to be located at the installation of the measures; the issues include missing insulation, condensation problems, etc.

³⁴ In the sample ($n=26$) only one property was found on the day of the visit to still be expecting roof insulation installation. The study has assumed that roof insulation has been installed in the property (TSB034) as planned.

a. Thermal imaging:

A small number of cases in the sample have thermal images from both the pre and post-refurbishment works that used in the analysis. Therefore in nine of the 26 cases the pre-refurbishment images have been used to detect the main problems in the existing building fabric that needed intervention; and in five cases of post-refurbishment, thermal imaging inspection has helped to evaluate the level of intervention and quality of installation works. Comparisons between the thermal images of the pre and post-refurbishment periods were not allowed in all cases in the study. Therefore in the properties with external insulation, comparison constraints between pre and post-refurbishment phases are due to the change of cladding material after the refurbishment works as well as the different external temperatures and times that the thermal inspections took place. Nevertheless, thermal tests have allowed the study to detect defects in some of the building fabric interventions and construction failures such as in the insulation, opening installation and thermal bridges. These issues were examined within the three clusters of insulation type (external, internal and mixed insulation) to have a more comprehensive view of the factors affecting building fabric performance and to discuss it in the following section along with airtightness tests and other building fabric characteristics.

From the pre-refurbishment thermal images of all types of wall construction four main problems with the building fabric were identified:

- significant air leakages around the openings (windows and doors);
- heat loss from the type of the openings (windows and doors);
- lack of wall insulation and insulation defects on walls' cladding; and
- cold bridges on walls edges and between the walls and roof.

For the properties with available data (n=16) the post-refurbishment thermal images have shown that fabric heat losses and air leakages have been reduced significantly compared to neighbouring buildings (see Appendix 18, Table 23). This is also demonstrated by the fact that in fourteen properties examined the temperature of the tested wall surface is close to the external ambient temperature, with a difference of less than 2°C (Figure 55). Generally, only in two cases – one with mixed internal insulation (TSB04) and another with external insulation (TSB027) – does the temperature difference exceed 2 degrees.

For the properties with external insulation, thermal imaging evaluation shows that all buildings' air leakages and heat losses have significantly improved overall. Only in single cases such as in TSB027 are still present minor insulation defects on the party wall with next building, or in case TSB044 there is a cold bridge in the window seal of one front window. Also in case TSB076 major problems were detected including cold bridges on walls edges and between walls and roof, as well as insulation defects on the walls. However, in this case such issues are explained by the fact that the insulation was installed three years before the RfF project when retrofitting works were undertaken in the estate following merely the regulation standards. Consequently no further insulation improvements were undertaken in this property by the RfF project on the walls. In the majority of the properties insulated externally the temperature difference is above 1 degree; and only in case TSB102 the internal and external temperatures are at similar levels (ambient temp. 6.3 °C, wall 6.6 °C).

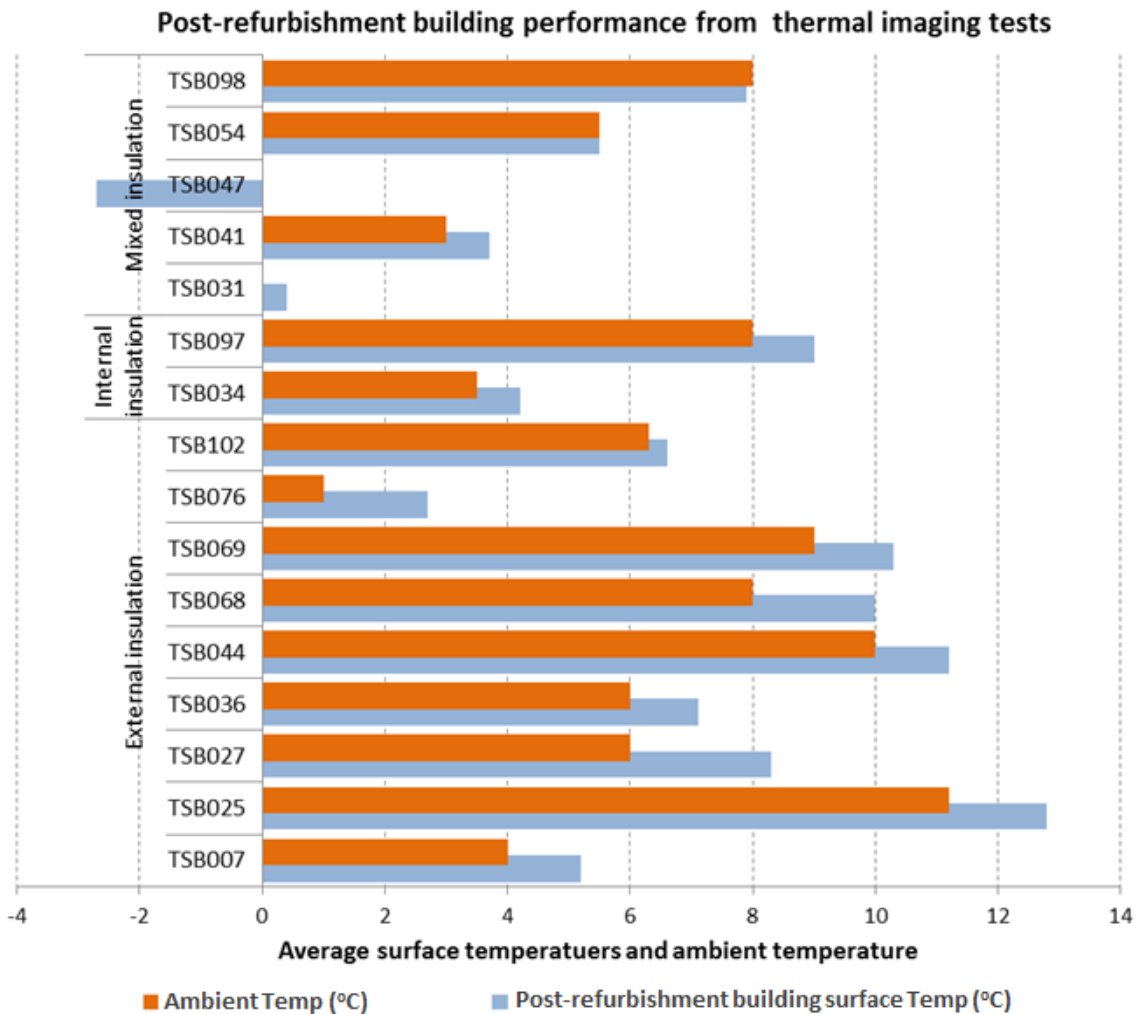


Figure 55: Comparison of the ambient temperature and buildings' fabric surface temperature in post-refurbishment thermal imaging tests.

For the cases with mixed insulation (internal and cavity fill or external and internal insulation), although the refurbishment interventions have generally improved previous building fabric problems there are still some issues with the installation of the insulation, especially for the cases with mixed internal and cavity fill (e.g. TSB031 and TSB047). In this cluster of cases, with walls that have been insulated internally, the figures of temperature difference appear to fall below 1 degree of difference except for TSB047. Finally, looking at the cases with internal insulation installed, the only defect identified in the thermal imaging is the cold bridge between the walls and ceiling, and in walls' edges; the temperature difference falls similarly to equal to or less than 1 degree.

Comparing the thermal imaging for the fourteen cases it was found that in the properties insulated externally the construction failures are minimised, with buildings' fabric having fewer defects overall, especially in thermal bridging. As regards the temperature differences, no major variation due to the type of insulation installed was found.

b. Airtightness tests:

The design standard set by the RfF competition for all properties in the sample required air permeability based on the SAP calculations, setting a threshold of less than $7\text{m}^3/\text{h}/\text{m}^2$ at 50Pascals. For almost all properties in the sample (25 of 26) the results from the actual pre-refurbishment airtightness test were compared with the post-refurbishment achieved after the low-carbon improvement work (see Figure 56 below). The pre-refurbishment pressurisation tests showed that more than half of the properties ($n=15$) in the sample were below $10\text{ m}^3/\text{h}/\text{m}^2$ at 50Pa ³⁵, whereas before low-carbon works only four properties were surprisingly already below SAP threshold airtightness levels. From the post-refurbishment tests it appears that nine properties with high levels of airtightness before the works had a significant drop of more than 50% after refurbishment interventions. More specifically eighteen cases are found below the SAP threshold, of which eleven ($n=11$, TSB047, 41, 40, 36, 07, 68, 69, 33, 110, 54 and 34) have also achieved best practice levels³⁶.

³⁵ The maximum air permeability of $10\text{ m}^3/\text{h}/\text{m}^2$ @ 50Pa is the building regulation standard and considered the poorest acceptable standard in the UK.

³⁶ The best practice recommendation aims for air permeability of $5\text{ m}^3/\text{h}/\text{m}^2$ @ 50Pa .

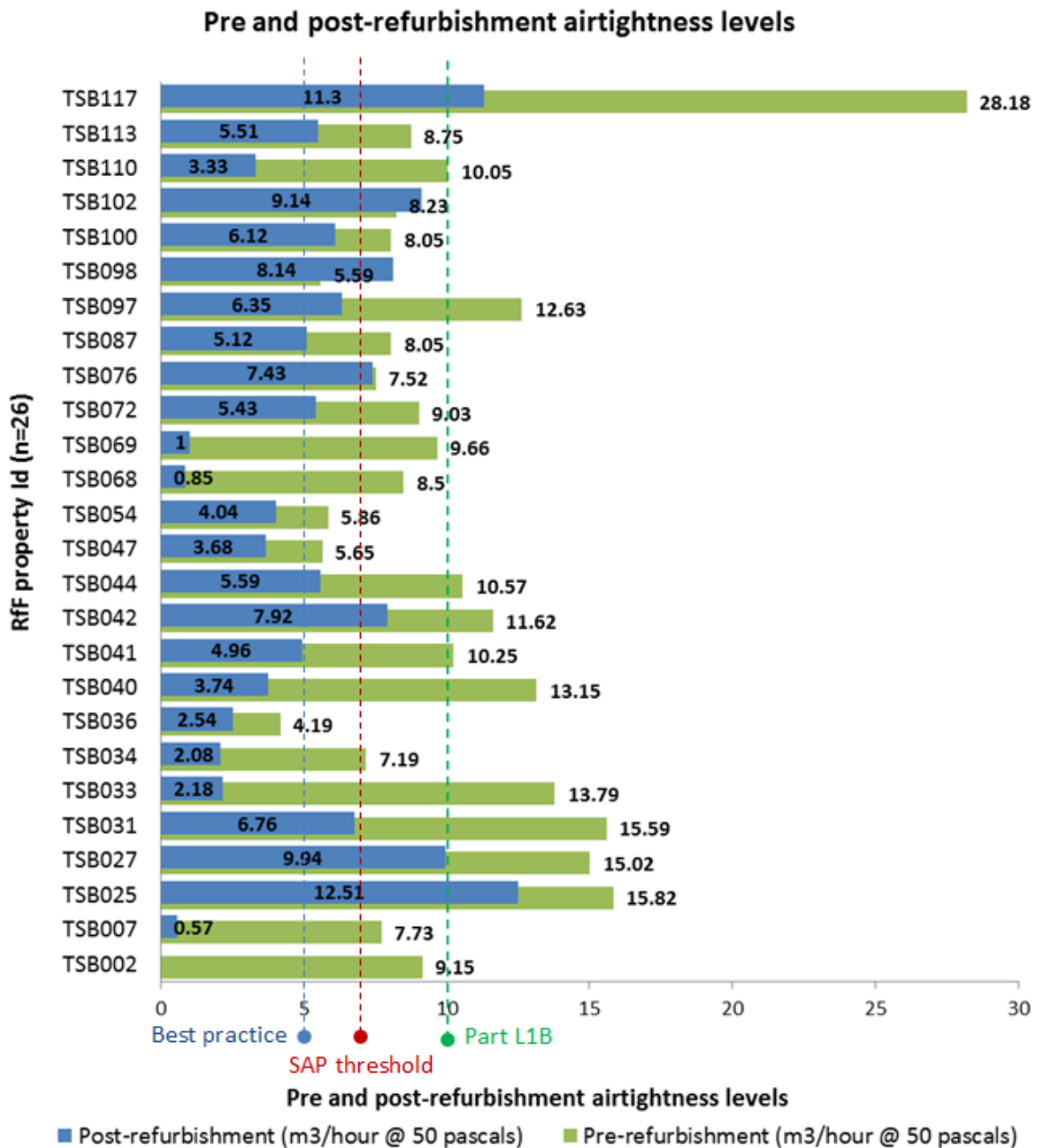


Figure 56: Airtightness levels in the pre and post-refurbished properties (n=26).

From the remaining seven cases above SAP levels, in only two properties TSB098 and TSB102, increased post-refurbishment compared to the pre-intervention works stage, by 45.6% and 11% respectively. In property TSB076 there was only a slight decrease of 1.2% from previous levels.

Looking at the eleven cases of best practice in terms of airtightness, together with thermal imaging tests and the low intervention measures undertaken in the fabric, it appears that

their airtightness has not been affected by the type of the openings (windows and doors) or whether for instance the external door has not been replaced and the floor not insulated (as discussed in Figure 53, p.231). However, the same levels of refurbishment interventions and high standard measures have been undertaken in the three cases with very low airtightness performance. In these cases this indicates construction failures, and clearly demonstrates that airtightness can be significantly improved not only by having a high standard design or a number of high performance measures but most importantly by having a high standard of implementation in the construction and installation of these measures.

In the following sections the systems installed for heating and ventilation are discussed clustered by the system's type and heating or ventilation sources and controls. From a technical perspective the discussion focuses merely on their non-interaction physical attributes and characteristics.

7.1.4 Buildings' heating systems and controls

There are four types of heating systems (see Figure 57 below and Figure 58) installed in the sample (n=26) combined with different low-carbon heating measures and controls (see Figure 58 below, Appendix 20 and Appendix 22). In the majority of the cases (n=9) gas boilers were installed for heating and hot water. In six properties the heating is provided by ground source and air source heat pumps, and in only four cases by domestic biomass boilers; in seven properties micro-CHP systems were installed not only to provide heating and hot water but also to generate up to 1kWe (kilowatts electrical) of electricity for domestic usage.

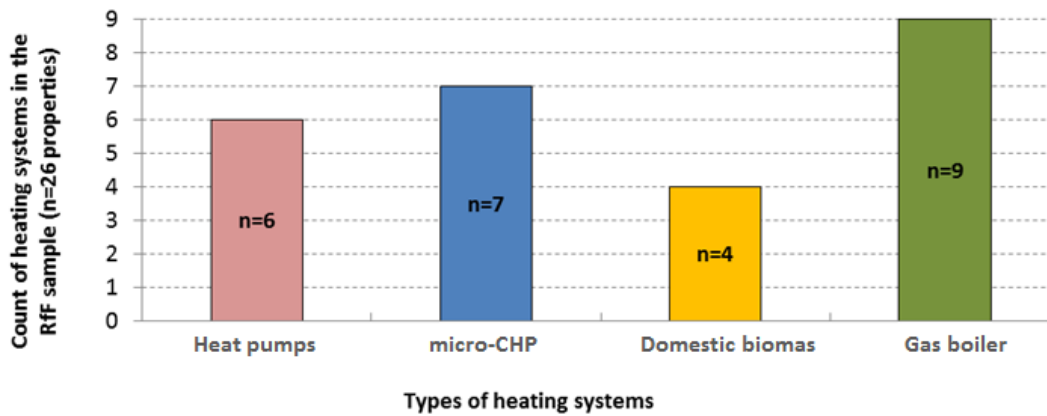


Figure 57: Different types of heating systems in the RfF sample (n=26).

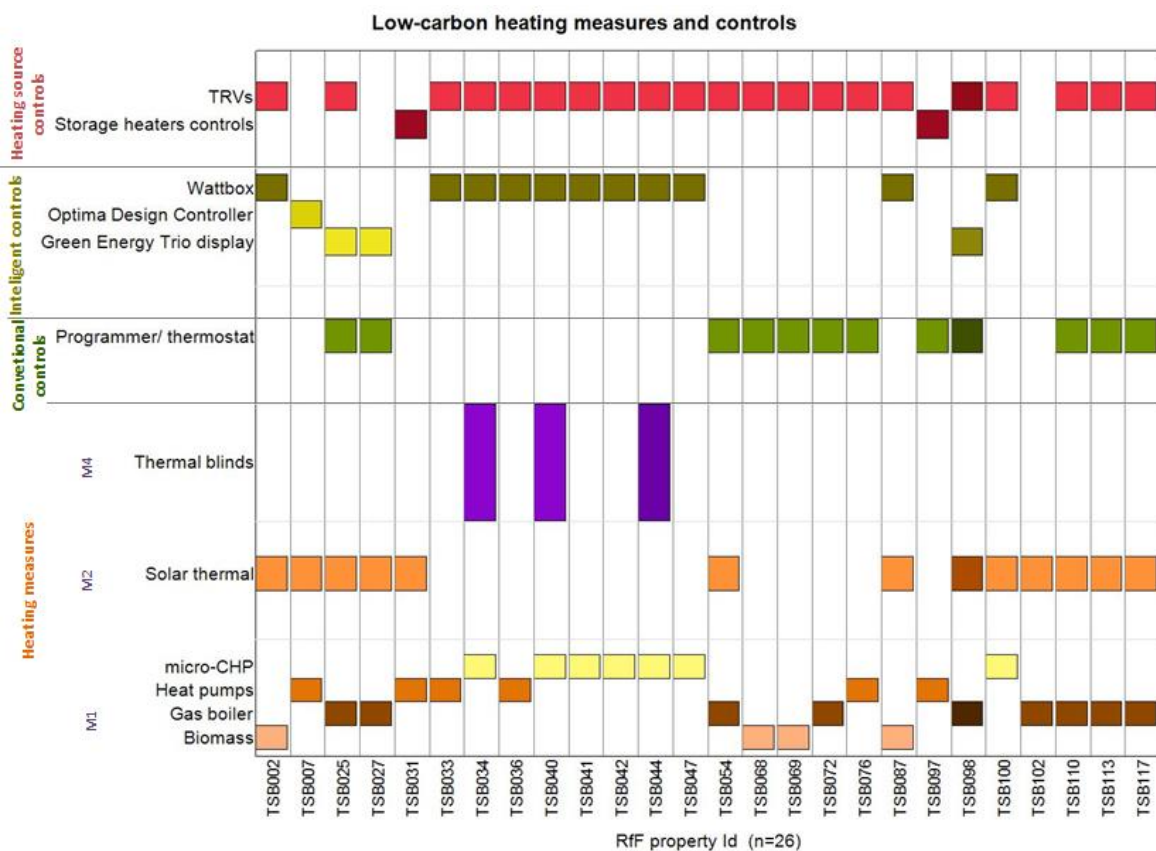


Figure 58: Low-carbon heating measures and controls (n=26).

As shown in Figure 58, in nineteen cases the heating systems were combined with photovoltaic panels for electrical generation and in half of them (n=13) solar thermal panels were additionally used as a back-up to the hot water heating system. In three properties with micro-CHP systems additional passive design measures like thermal blinds were also installed.

The heating controls in the majority of the properties (n=14) are different types of intelligent controls such as Wattbox and Optima Design controller; the rest of the cases (n=12) have conventional controls like programmers and thermostats. Only in two cases in the sample have storage heater controllers been the option to control the heating source (storage heaters); the majority of the cases have radiators with thermostatic radiator valve (TRV) controls.

a. Gas boiler heating systems and conventional heating controls:

In nine properties (out of 26) A+³⁷ rated gas boiler systems were installed (Appendix 20, Figure 148 - Figure 150) for heating with conventional controls³⁸ like thermostats and programmers. There is one property with a communal gas boiler system, but in most of the properties (n=6) a condensing gas boiler system was installed and only two properties in the sample have combi gas boilers. The different types of gas boiler systems and heating sources in the nine properties examined are illustrated in the Figure 59 below.

There is also one property the existing boiler was kept as it had been replaced a couple of years before the RfF works took place³⁹.

³⁷ Boilers' rating system is based on Sedbuk (Seasonal Efficiency of Domestic Boilers) in the UK. This is a system that classifies and compares boilers on their efficiency to convert fuel into heat. The rating scale is from A to G, with A being the best and most efficient (90% and above efficiency) and G the lower below 70% efficiency.

³⁸ Conventional heating controls include room thermostats, central heating programmers with central heating timer switch and thermostatic radiator valves.

³⁹ In 2005 Building Regulations set as a requirement that all domestic boilers newly installed or replaced need to be high efficiency condensing boilers. The advantages of condensing vs non-condensing boilers are: in the combustion with condensing boilers be fully room sealed taking air directly from the outside through the flue and not from inside the room; at least 25% more efficient than non-condensing boilers meaning reducing energy costs; have lower carbon emissions reducing households' carbon footprint substantially; and are supported with grants from policy schemes incentives.

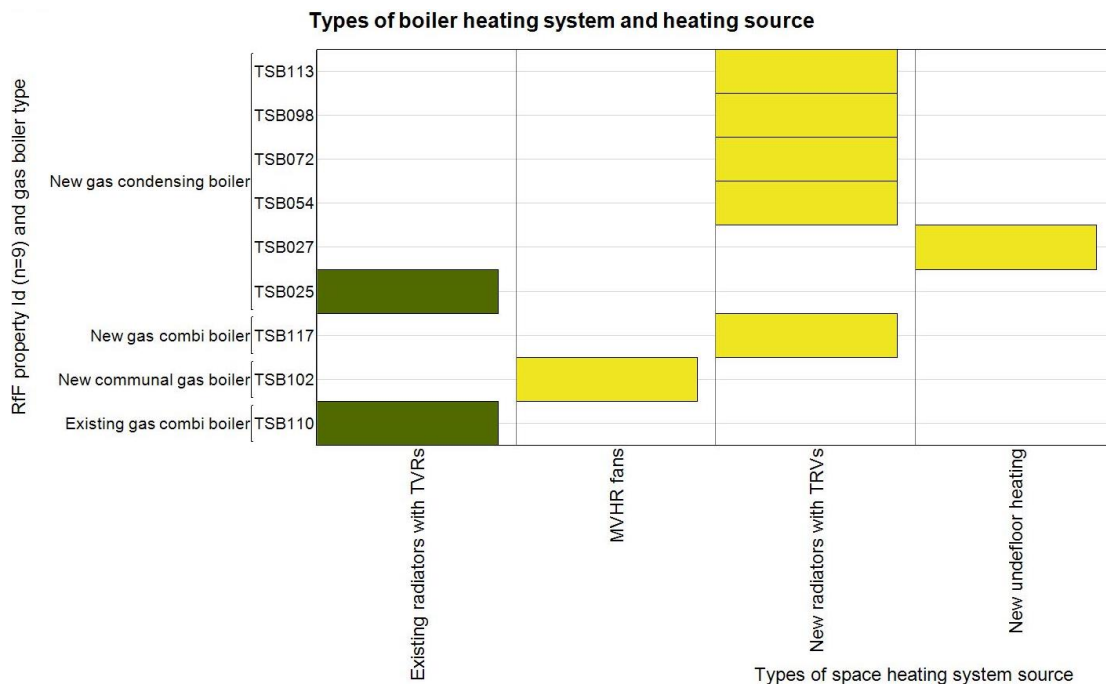


Figure 59: Different types of gas boiler and heating systems sources (n=9).

In most of the properties (5 of 9 cases) with gas boilers, new radiators with TRV controlled heating were installed. Only in two of the nine cases were the existing radiators kept. In the property with underfloor heating (TSB027) individual thermostats were installed in each room; and in the case of TSB102 the MVHR fans are used as a heating source controlled by the central programmer and individually in each room by the filter fans.

b. Micro-CHP heating systems and intelligent controls:

In all seven cases with domestic micro-CHP the same type of a high efficiency⁴⁰ unit was installed (Appendix 20, Figure 151). The heating and hot water controls from micro-CHP are managed via the intelligent control system Wattbox; in all cases the heating source is radiators with TRV controls. In three properties (TSB044, 040, 034) in this cluster the heating strategy also included the installation of another passive measure, thermal blinds, in all windows of the properties.

⁴⁰ Overall efficiency of micro-CHP unit, (Baxi Ecogen) 92%, electricity output 1.1kW and thermal output 24kW.

c. Heat pump heating systems and controls:

There is a variety of heating sources and controls in the properties with heat pump heating systems (Figure 60).

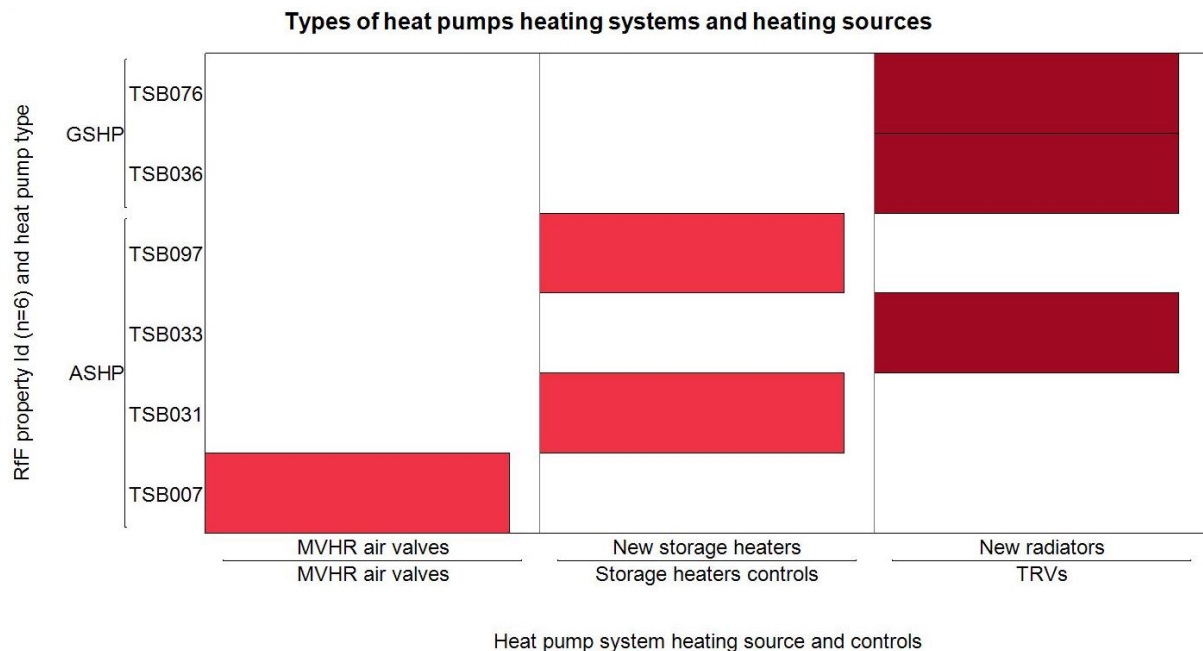


Figure 60: Different types of heat pumps as heating systems, sources and controls (n=6).

In the two properties with ground source systems (GSHP), Wattbox intelligent controls and radiators with TRVs were installed in all rooms. There is a wide variation of heating sources and systems’ controls in the properties (n=4), with air source and air to air source heat pumps (ASHP) (Appendix 20, Figure 146 and Figure 147). Therefore the systems’ controls were found to vary from conventional programmers and thermostats to intelligent controls combining MVHR systems to deliver space heating. Again the source controls for these cases vary from conventional radiator controls (TRVs) to more advanced storage heaters controllers and controls on the source of MVHR air valves.

d. Domestic biomass boiler heating systems and controls:

Domestic biomass wood pellet boilers were installed only in four properties out of 26 in the sample to provide heating and hot water (Appendix 20, Figure 144 and Figure 145). In

half (n=2) of the properties Wattbox intelligent heating controls were installed, whereas in the other half the controls are operated through conventional programmers and thermostats. In all cases the heating source is new radiators with TRV controls in all rooms.

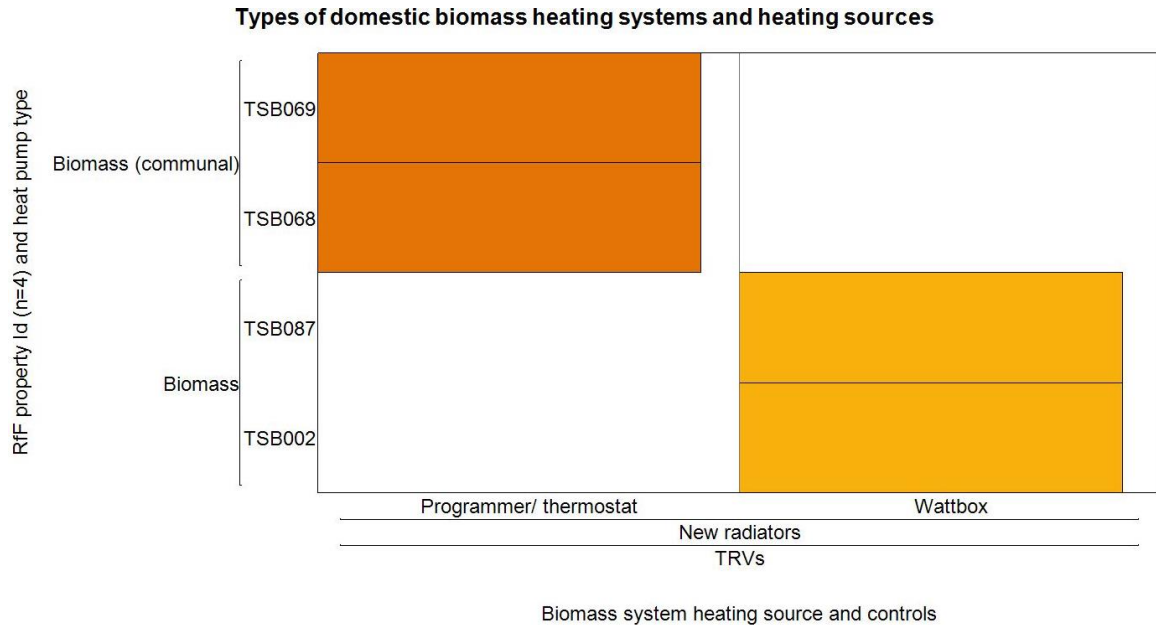


Figure 61: Wood pellet biomass heating systems, source and controls (n=4).

From the 4 properties with biomass as the heating system, the pair of semi-detached houses (TSB068, 069) share a communal wood pellet boiler located in a separate storage space next to the properties together with a pellet store/hopper and auto feed system; in both other properties (TSB087, 002) the boiler is manually fed and is located inside the house (in the living room and utility room).

e. Solar technology

Solar technology was installed for hot water heating (n=14, solar thermal panels) and electricity generation (n=19, photovoltaics PVs). In thirteen properties a combination of both was installed. In five out of 19 properties small size photovoltaic panel array of 1kWp (Kilowatt peak) for onsite electric production was installed, whereas in 8 properties (of 19)

the electric production is by panels greater of 2.1kWp (Figure 62). However, in some cases the estimated electric generation does not correspond to the photovoltaic size as it's highly dependent on the orientation and location of the array panels.

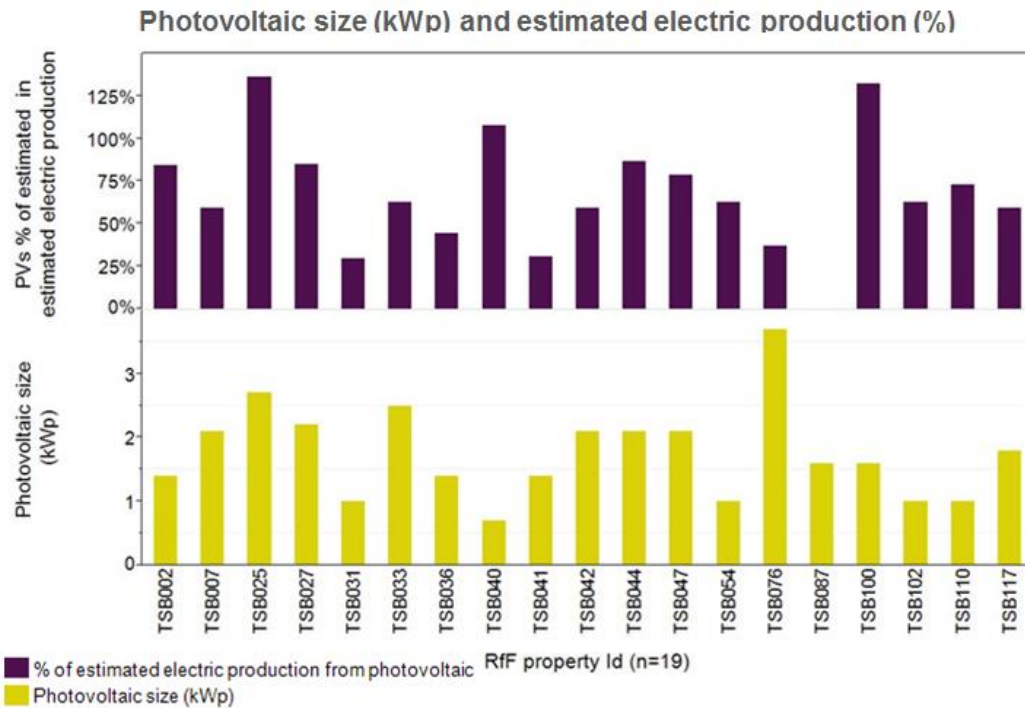


Figure 62: Photovoltaic size (kWp) and estimated electric production (%) (n=19).

7.1.5 Mechanical ventilation systems

Mechanical exhaust ventilation (MEV) systems and exhaust ventilation systems with heat recovery (MVHR) were installed in all 26 properties (Appendix 21). In five properties conventional MEV electric fans were installed in the wet rooms (kitchen and bathroom); in the rest of the sample (n=21) MVHR filter air valves were installed in all rooms complying with Passivhaus requirements. Only in one case were MVHR filters solely installed in the wet rooms (bathroom, toilet-shower and kitchen), controlled by on/off switches (Figure 63).

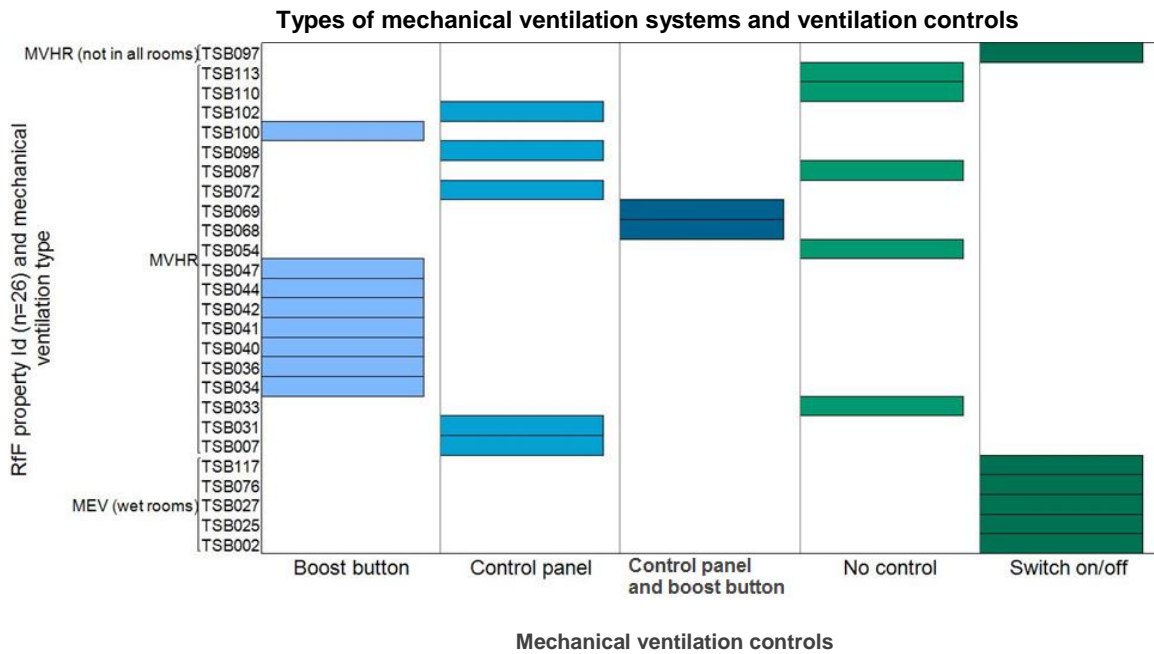


Figure 63: Different types of mechanical ventilation systems and controls (n=26).

The MVHR controls in the rest of the sample (n=20 properties) vary from single boost button switches installed to boost the system’s operation for 30min and control panels with different settings for fan speed, to cases with no controls installed (n=5 properties). In these properties the type of MVHR air valves for extract and air supply ranges from wall throw directional and ceiling or wall mounted air valves to filter extract valves, with this latter type mainly installed in the wet rooms.

7.1.6 Technical constraints of systems and measures

From a technical perspective it is important to understand and define to what extent the interaction with measures and systems in the 26 refurbished properties was initially ‘scripted’/prefigured solely by their design (Appendix 19, Table 24). This process allows an examination in the next chapter of what is exclusively due to occupants’ interaction with heating and ventilation controls.

The study considers that in all systems installed measures' controls were designed for either direct or indirect interaction that involves either active or passive⁴¹ users. Therefore in heating systems as shown in Figure 64, direct controls on gas boilers were designed for active users, whereas in biomass boilers, micro-CHP and heat pumps the controls were designed for passive users. The systems are indirectly controlled by measures like typical thermostats and programmers or innovative intelligent control systems (e.g. Wattbox, Optima Design Controller), all designed for active users. Additional measures installed for space heating such as the thermal blinds have been designed with direct controls for active users.

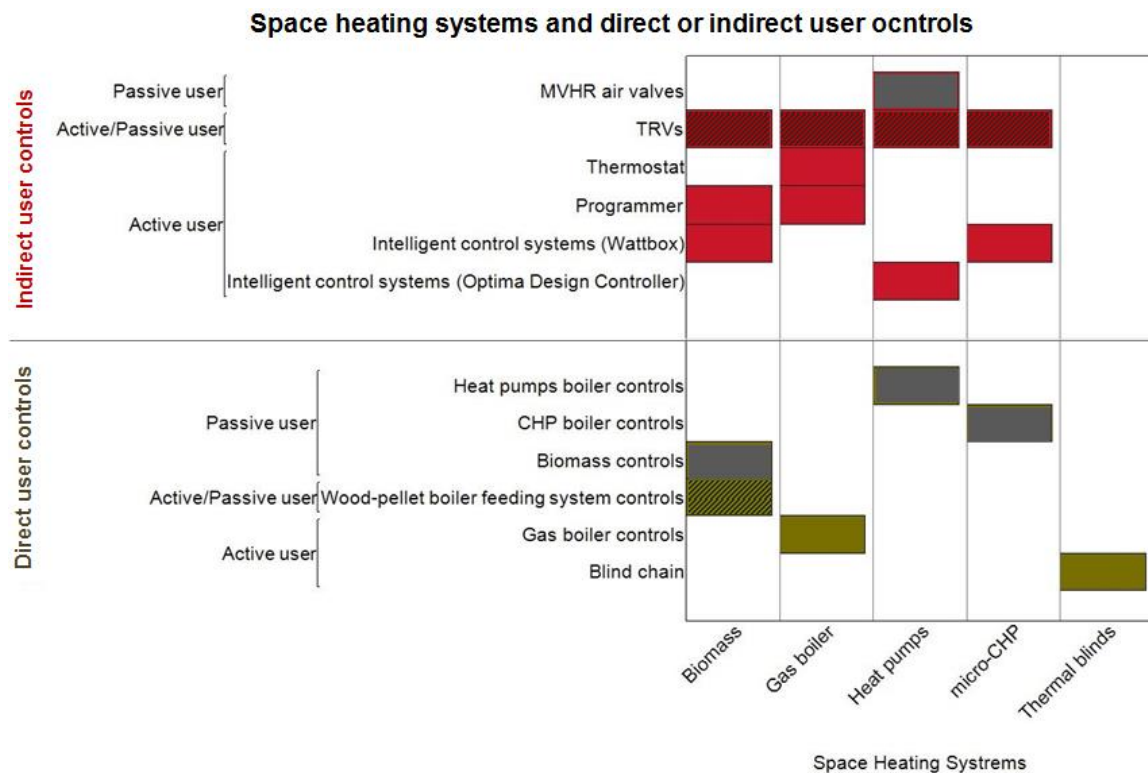


Figure 64: Space heating systems and direct or indirect user controls.

As regards the hot water systems in the 26 properties this is provided by the same heating systems or a combination of systems, such as a gas boiler system combined with solar thermal panels. Figure 65 shows that the direct controls are similarly ‘scripted’/prefigured

⁴¹ For the definition of the terms ‘direct /indirect interaction’ and ‘active passive user’ as used in this study see the study’s *Key definitions* section.

as in heating systems, allowing active users to interact only with the gas boiler controls, whereas indirect controls are all designed for active users.

Regarding the natural ventilation systems, all direct and indirect controls are designed for active users except the measure undercut door gap designed for air circulation in three properties, which prefigures passive users' controls (Figure 66).

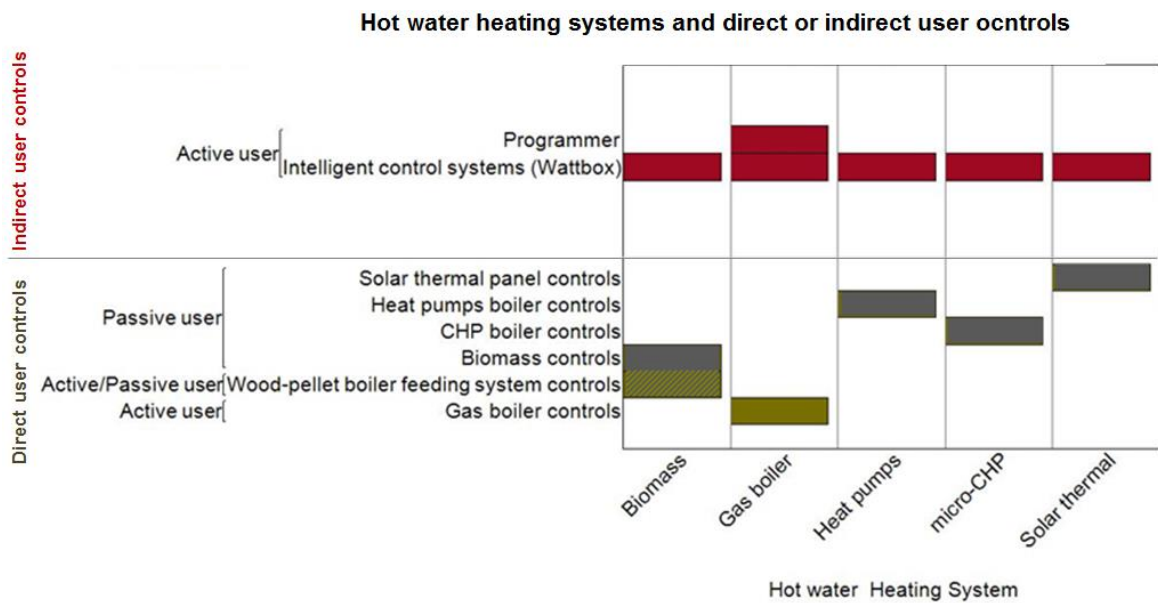


Figure 65: Hot water heating systems and direct or indirect user controls.

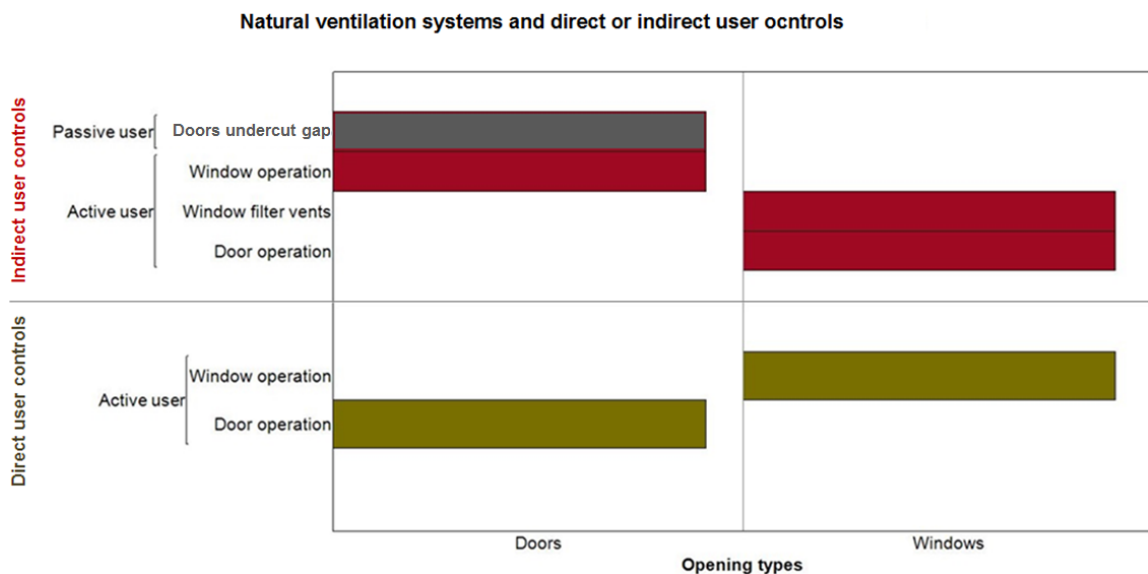


Figure 66: Natural ventilation systems and direct or indirect user controls.

Finally, the design of conventional MEVs' air extract systems in the sample allows active users' direct control. Only in cases where combined controls are installed (e.g. fan and light controlled by one switch) this indirect operation of the system involves passive users.

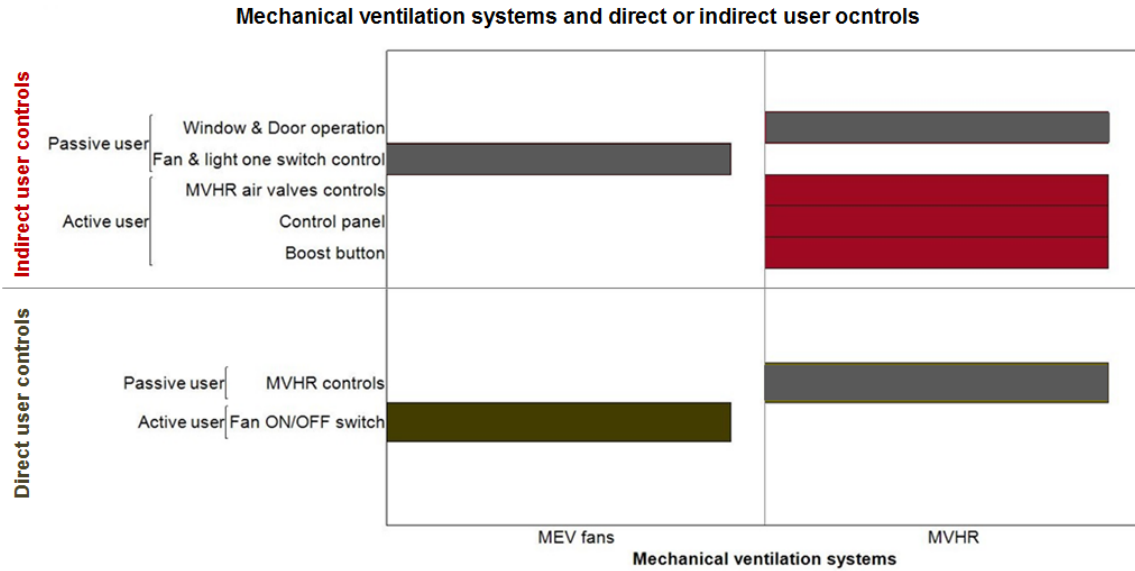


Figure 67: Mechanical ventilation systems and direct or indirect user controls.

In mechanical ventilation systems direct MVHR unit controls are not provided in any of the properties, while indirect controls involve the MVHR control panel, boost button and air valve controls, all provided for active users (Figure 67). Also, at the design stage in terms of the indirect impact from windows and doors operation in the MVHR systems in cooler months, this has considered passive users with openings (windows and doors).

7.2 Household system characteristics

The non-technical determinants related to occupants' personal aspects in the RfF households are discussed in this section. Three main clusters were considered in the sample that include demographic, economic and occupancy factors. The variables that emerged from the analysis of these factors are those that indirectly affect a household's energy use and an occupant's interaction with heating and ventilation.

7.2.1 Socio-demographic determinants

The socio-demographic and socio-economic variables discussed in this section are the number of occupants, the occupants' ages, family composition, living space per capita, occupants' cultural background, their qualifications and household income.

The structure of social housing households in the sample was split into four main groups: single parents, single occupants, couples and families. The occupants' ages were also divided into separate groups: one that includes adults' ages as the main permanent households' occupants and a second with the children⁴². For a couple of cases in this second age group it was found that child occupants between 18 and 50 years of age had a temporary or more interrupted occupancy in the RfF property. From the data it can be seen that the majority of the properties (17 of 26) in the sample are occupied by families and most (n=13) by 4 to 7 occupants (Figure 68). There is a smaller number of cases where the household consists of couples, single occupants and single parents. In only a few cases of single parent households (TSB087) the maximum number of four occupants is reached, whereas in the rest there are 2 to 3 occupants. Correlation was found between the family composition and occupants' age band. Therefore the majority of the occupants are between their 30s and 50s (n=14 cases) with children above 5 years of age (n=10). The age band for all households with a single occupant or couple (n=6) is above 50s; in only four households (3 with single parents and 1 family), the adult age group is below 30s and their children are of varying ages. Factors like the number of occupants and household age band will be discussed in the following section together with households' occupancy variables.

⁴² The children age group also includes older ages (18 to 50 years old) of main occupants' children that due to redundancy and economic reasons the period this study was undertaken were living temporarily in the property without having contribution to the household's financial expenses.

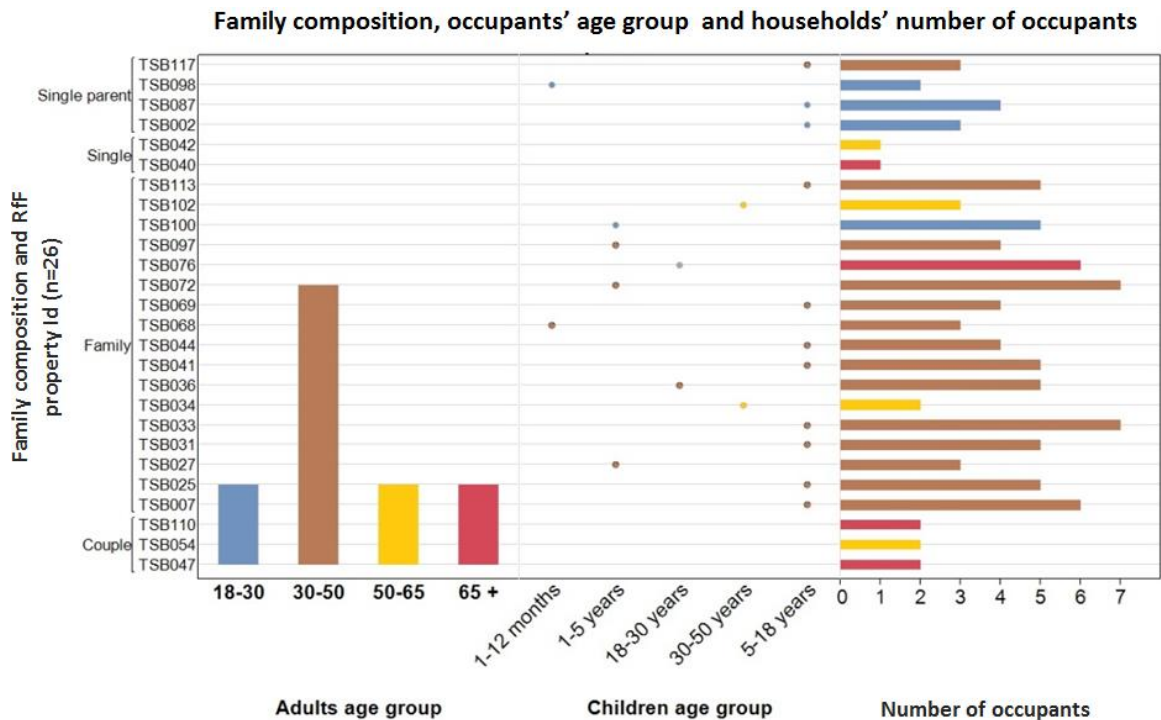


Figure 68: Demographic characteristics: Family composition, number of occupants and age in the RfF sample (n=26).

In order to understand the household's density in the refurbished living space the study also includes the number of occupants of a household in relation to the property's total floor area. Figure 69 shows that in the majority of the cases there is a strong relationship between the floor area and the number of occupants living in the properties. The cases (n=9) with an average total floor area of 60 to 80 square metres (band B) are occupied by two to four people, mostly small or single parent families; and only two of those are occupied by 50 plus couples. The rise in floor area in band C (n=12) and band D (n=4) is associated with an increase in the number of occupants (3 to 5 and 6 to 7 respectively), mainly occupied by families with children. Despite this, in TSB042, TSB047 and TSB110 no correlation appears in the floor area per capita; this can be explained in part by the qualitative data. Thus in case TSB042 another family member was expected to live in the property a couple of months after the day of the interviews; and in cases TSB047 and 110 most of the time there is increased occupancy from family visits, especially during weekends.

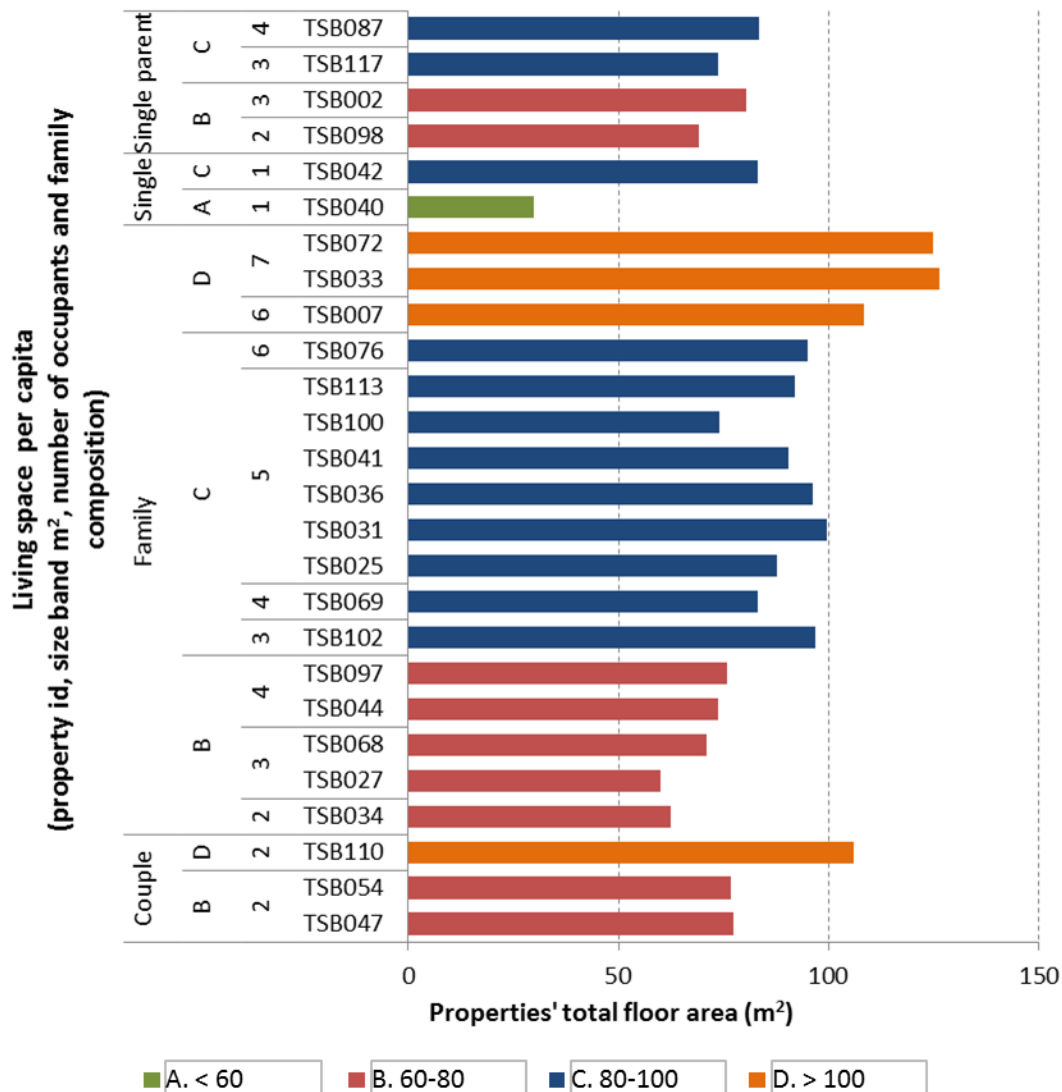


Figure 69: Living space per capita (n=26).

Two main allocation factors for moving into the RfF refurbished social houses were found in the sample. In most of the cases this involves social tenants' family needs for a different size of property; however, occupants' health conditions also often caused them to move to an improved indoor building environment.

Three groups of occupants' cultural background were found in the sample. As shown in Figure 70 below, the majority of them are white British and only 11 and 4 per cent are black and Asian respectively. This factor will be considered in the following Chapter 8 in relation to occupants' heating and preferences to regulate their comfort.

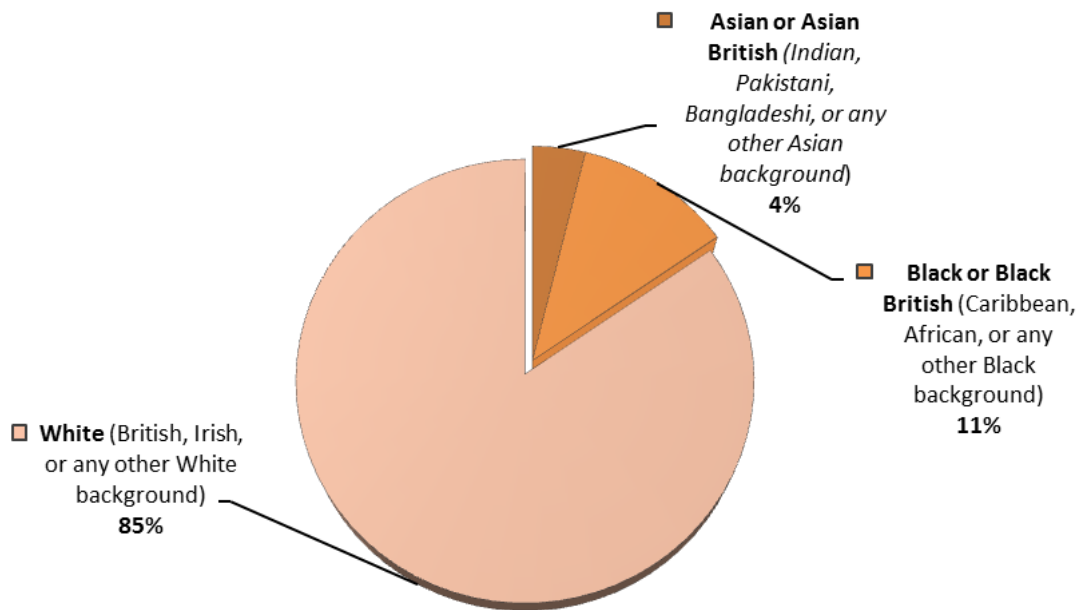


Figure 70: Occupants' cultural background (n=26 properties).

Occupants' qualification level was examined in relation to their knowledge of buildings and construction, computing or in other relevant sectors that could affect the ways they operate controls or affect their understanding of the low-carbon interventions and measures installed. Figure 71 shows that there is a very small number of households in which at least one occupant has qualifications related to buildings and controls (e.g. plumber, builder, solar technology installer, computer scientist etc.). Nonetheless, this factor will be discussed in the following chapter in relation to the training provided to the occupants on the installed measures, and to their past-experience and tacit knowledge from previous buildings' controls.

The study has evaluated households' economic status in relation to energy bill payment and whether bills are paid by the occupants or by other parties (e.g. housing association, council, etc.). Households' income was divided into four groups as defined by overall income of the family; these groups range from a lower economic band, level 1, to a higher level 4.

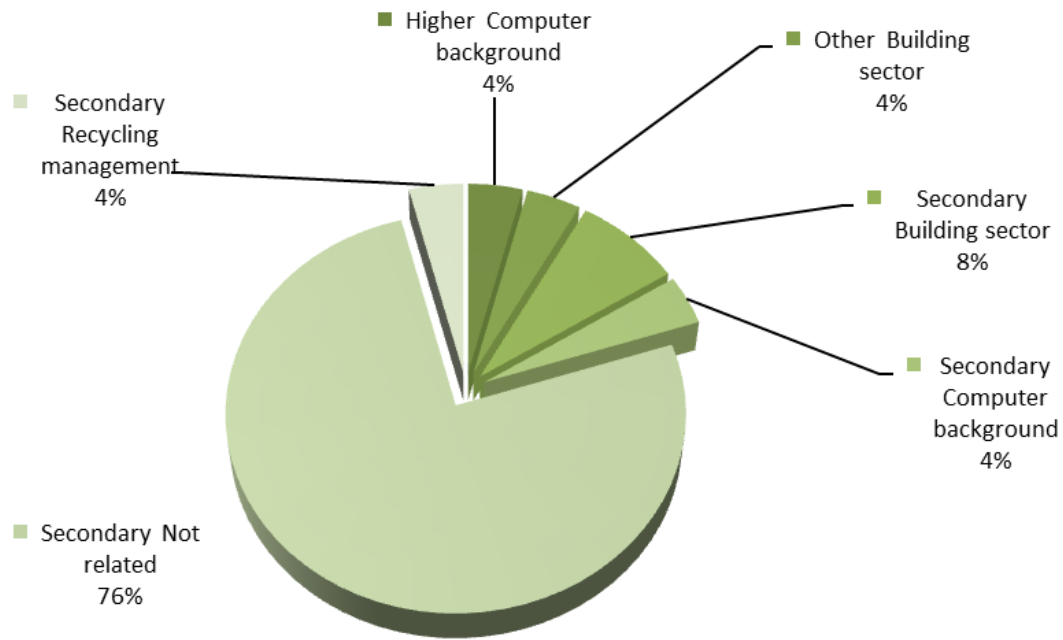


Figure 71: Education level and occupants' qualifications related to buildings and controls (n=26 properties).

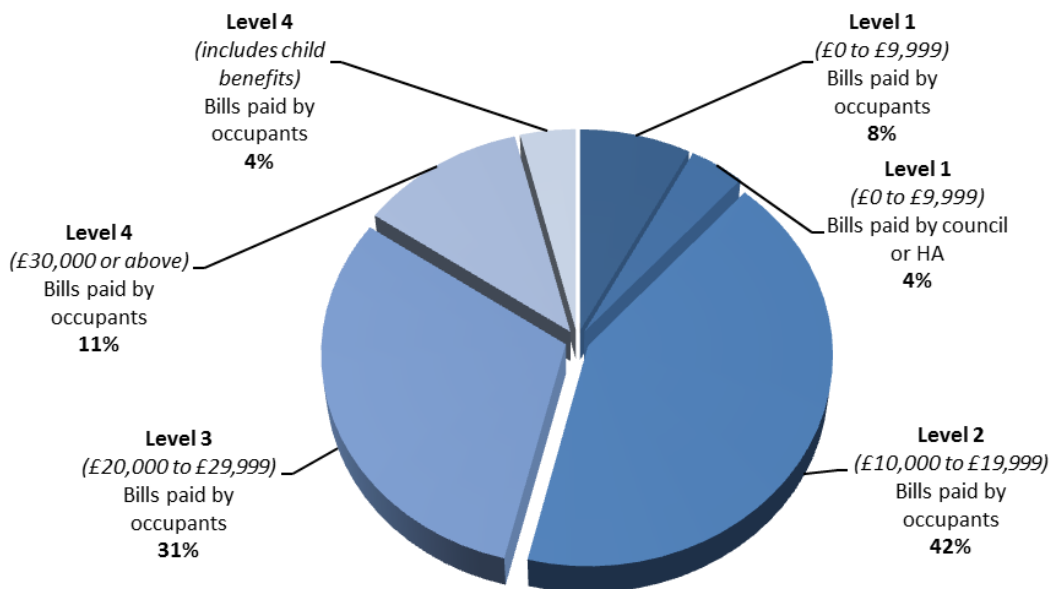


Figure 72: Economic status of the RfF households, with annual income (n=26 properties).

Figure 72 shows that the majority of the households are in the economic band corresponding to levels 3 and 2; only a small number of households are in the lower band at level 1 (n=3 cases) or in the higher level 4 (n=4 cases, of which one case includes also

benefits). Except for one household, whose energy bills are paid for by the housing association, the bills are paid by the occupants (adults' age group).

The distribution of these income groups will be examined in the core analysis in Chapter 8 together with the household's energy costs in the pre post-refurbished environments. This will give an indication of the level of occupants' awareness of using energy and of the factors affecting their past and post-refurbishment experience with heating and ventilation controls. Other social variables like occupants' occupations are discussed in terms of length of house occupancy in the following sections.

7.2.2 Non-technical micro-factors

A significant factor that the study has found to be related in the RfF sample to occupants' characteristics is health. In half of the cases (13 of 26 households), one or more occupants has a health issue or condition. The study has considered two groups of health conditions: one that includes only the cases where an occupant's health condition is related to or is directly affected by the building environment, and another in which an occupant's health condition affects his or her interaction with the building environment.

In this respect it was found that in seven properties health issues like asthma, chest infections and rheumatism had appeared or deteriorated due to the poor pre-refurbished building environment.

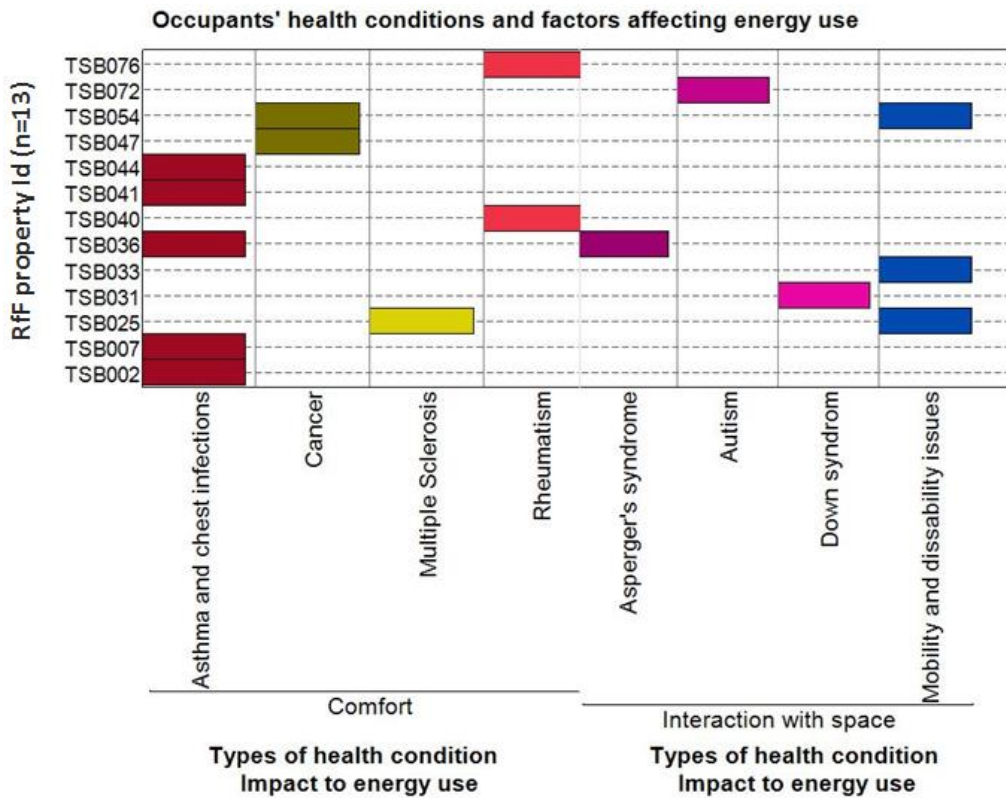


Figure 73: Occupants' health conditions and factors affecting households' energy use (n=13).

Within these two groups are occupants' health conditions that are related to the indoor comfort levels affecting their interaction and practices in heating and cooling, as well as also health issues affecting occupancy and the ways occupants interact with the indoor space (Figure 73). Such issues are discussed in Chapter 8, focussing on the correlations between health and occupants' interaction and energy use before and after refurbishment.

The study has also considered occupants' other individual micro-factors that shape the overall households lifestyle. Therefore, factors that affect indoor comfort levels and CO₂ levels and consequently users' interaction with ventilation (natural and mechanical) measures are occupants' smoking habits, as well as the number and type of pets living in the house. As regards the smoking habits, from the qualitative data (in-depth interviews) it appears that fifteen of the 26 households have one or more smoking occupants.

In only two cases are occupants smoking indoors and the majority of them are smoking outside the house (Figure 74). What occupants say and the effect that smoking has on indoor air quality and energy use are cross checked and examined with the physical monitoring metering in the following chapter.

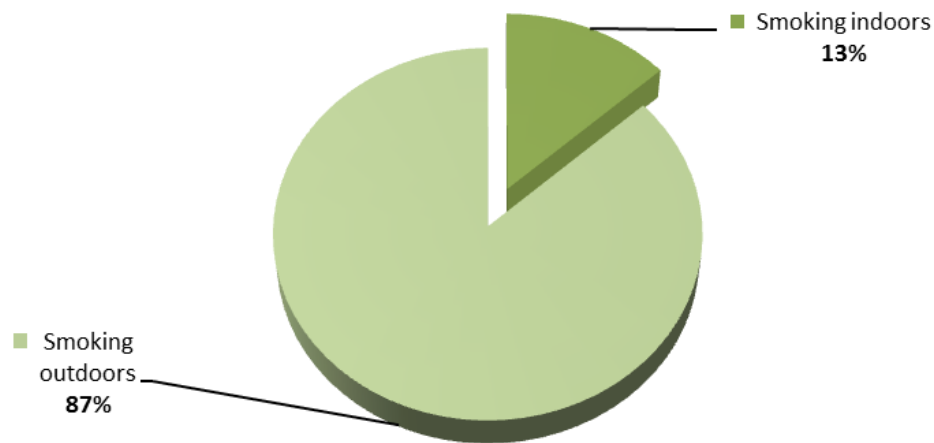


Figure 74: Occupants' smoking habits (n=15 properties).

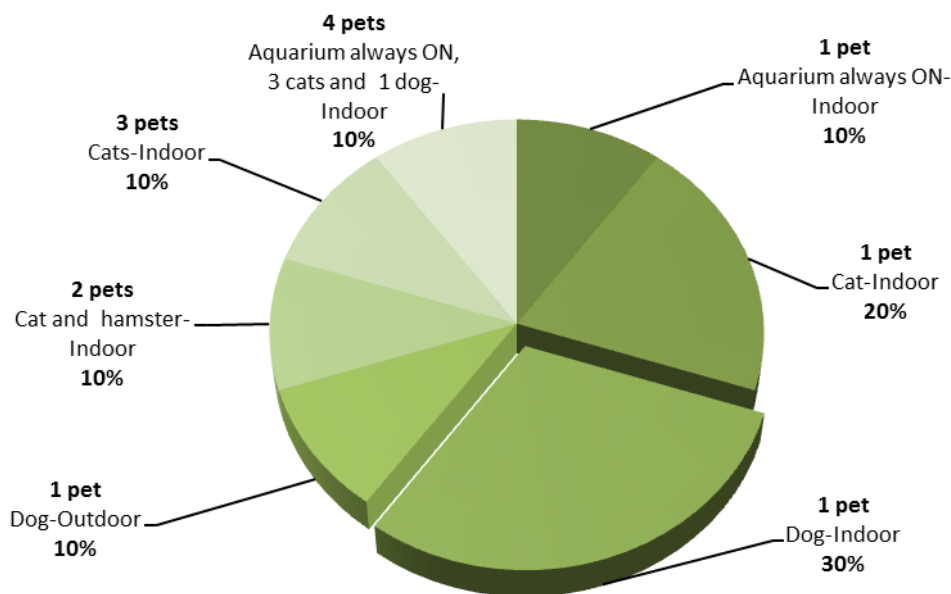


Figure 75: Households with pets (n=10 properties).

As regards the households with pets, the dog lives outdoors in only one case out of the 10 households with pets. In the rest of the properties the number and type of pets vary and all live indoors. In the households with cats no cat flap in any of the external doors was found.

There are two cases in the sample with aquariums that are always ON and this aspect is considered in households' energy consumption in the following chapter. For the two cases (TSB076 and 034) with available quantitative data on openings' operation, correlations with occupants' smoking habits and pets' practices are also examined.

7.2.3 Occupancy background

A factor that was found to affect occupants' post-refurbishment experience in the sample is households' occupancy background (past-experience) in the RfF houses and whether they were occupants before the installation works or moved in after the low-carbon works finished. For those occupants who were living in the property before the works, it was also examined whether they had been relocated or lived in the property during the refurbishment interventions. This section discusses occupancy characteristics to draw the occupancy background for each household. The correlation and the effect that these factors have on occupants' post-refurbishment experience living in the RfF property are presented in the following chapter.

There are two main groups in the sample, consisting of the occupants who are new to the property and those who were living there before the RfF refurbishment works. In twelve out of the 26 properties occupants are new tenants who moved into the refurbished RfF properties after the installation works; for the rest of them (n= 14), occupants were living in the property before the RfF works (Figure 76). From this latter group only 8 households had the experience of living in the property the whole time refurbishment works were taking place; those with health issues, families with young children and elderly occupants were relocated to other properties during the installation time.

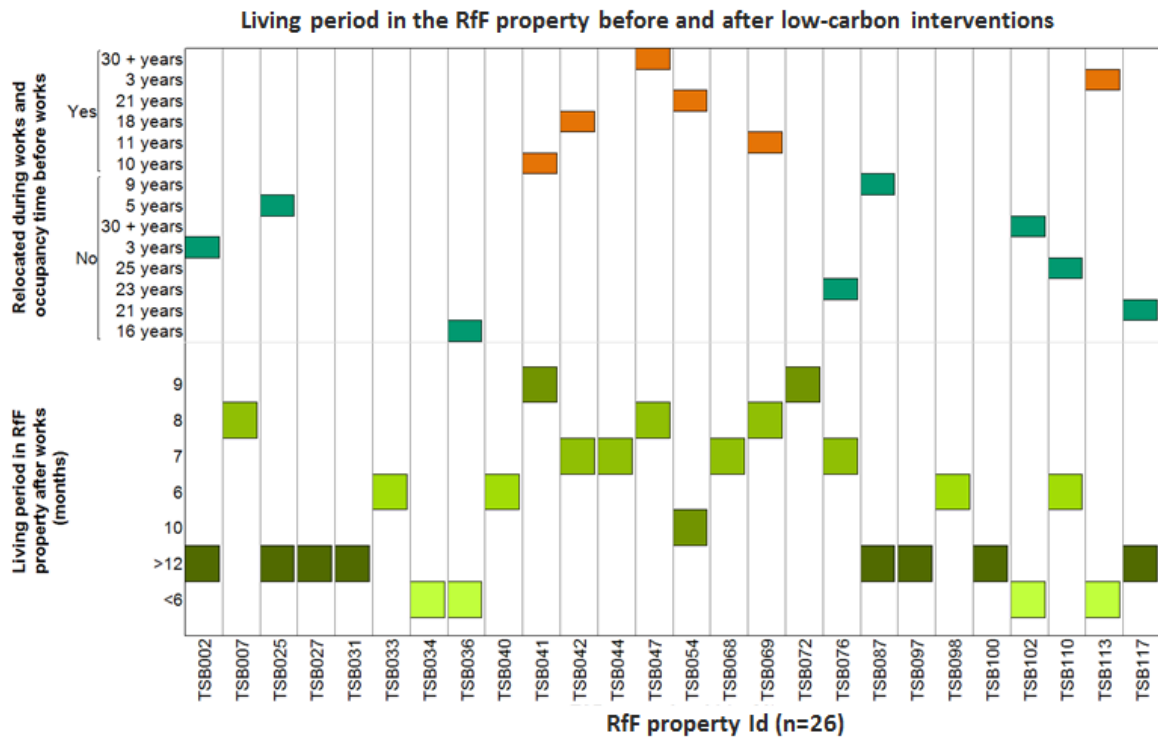


Figure 76: Occupants living in the RfF properties before and relocation during refurbishment (n=26).

While the past period of living in the RfF property can vary from a minimum of three years to more than thirty years, the post-occupancy experience in the refurbished property for the 26 households up to the day of the interviews was from five months to over one year. The study considers three main groups of post-occupancy time in the sample (groups with variations of green in Figure 76). The first comprises the few occupants who lived in the property for less than 6 months, the second those who lived in the property from six to eight months, and finally the last group those occupants who lived in the refurbished property for more than nine months. The relation of these groups to factors affecting occupants' post-refurbishment experience in the RfF properties is discussed in Chapter 8.

Households' occupancy in the sample has also been seen in relation to the heating and cooling period for the UK, which considers the heating season to last from January to March and October to December (DECC, 2013b). Figure 77 shows that the majority of the properties have experience of at least two heating months.

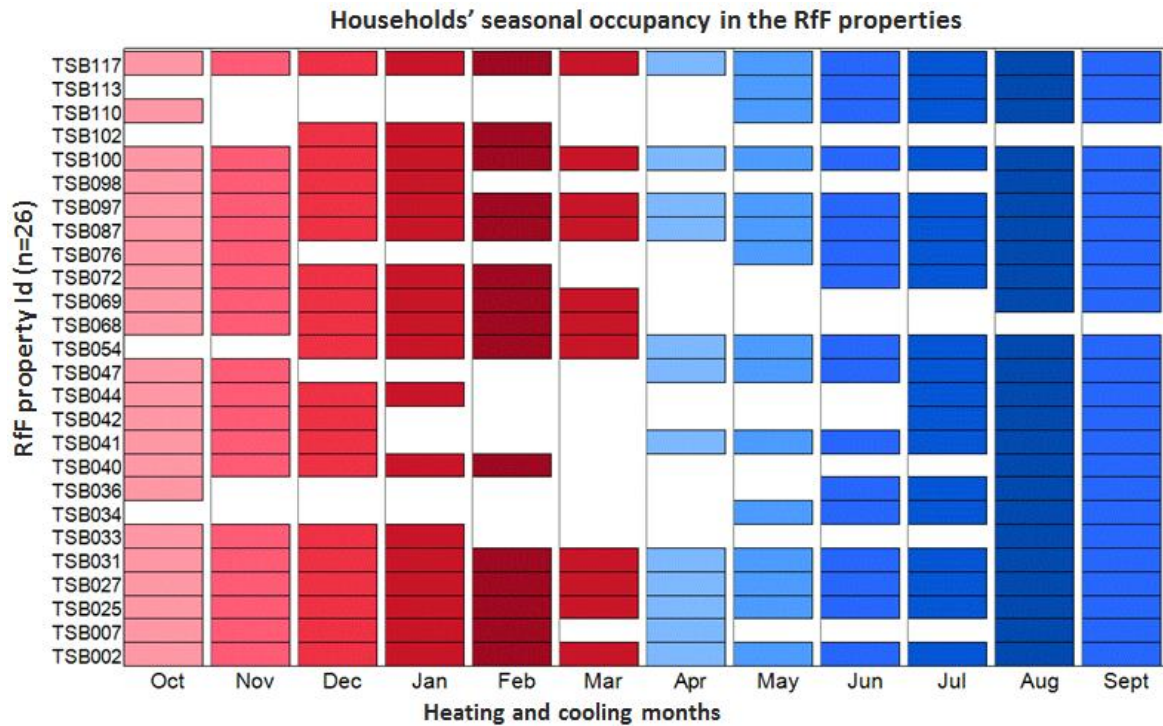


Figure 77: Households' seasonal occupancy of heating and cooling periods in the RfF properties (n=26)

In just four cases (n=4, TSB034, 036, 110 and 113), which also featured new occupants of the RfF properties, time of occupancy includes either no or one year's heating experience in the refurbished property. There are five cases (n=5, TSB100, 025, 027, 087 and 117) where occupants' heating season experience in the RfF property lasted more than one year. This aspect was examined in relation to variables in post-refurbishment and past-experience with and ventilation controls and different interactions were compared within the two groups (occupants before and after refurbishment).

7.2.4 Post-occupancy patterns

Assessment of households' occupancy patterns requires information about the number of the occupants, the time of occupancy and the occupied space. The qualitative data from the interviews has provided a household's average time of occupancy on a weekly basis (weekdays and weekends). This will be compared with the physical data (heating fuel

consumption, room temperature, CO₂ and humidity) to cross check occupancy patterns and to indicate households' heating and ventilation usage.

Correlations were found in 23 cases between the three groups of occupation type (full time, part time and not working) and the time in which the house is occupied by one or more users during a day of a typical week (Figure 78). High occupancy was found in the group in which one or more occupants of the household are not working (n=11 including cases with pensioners). The properties in this group are occupied from 22 to 24 hours, with someone always staying in the house. Deviation in this group was found only in one case (TSB040), in which the occupant, though retired, is out of the house for most of the day.

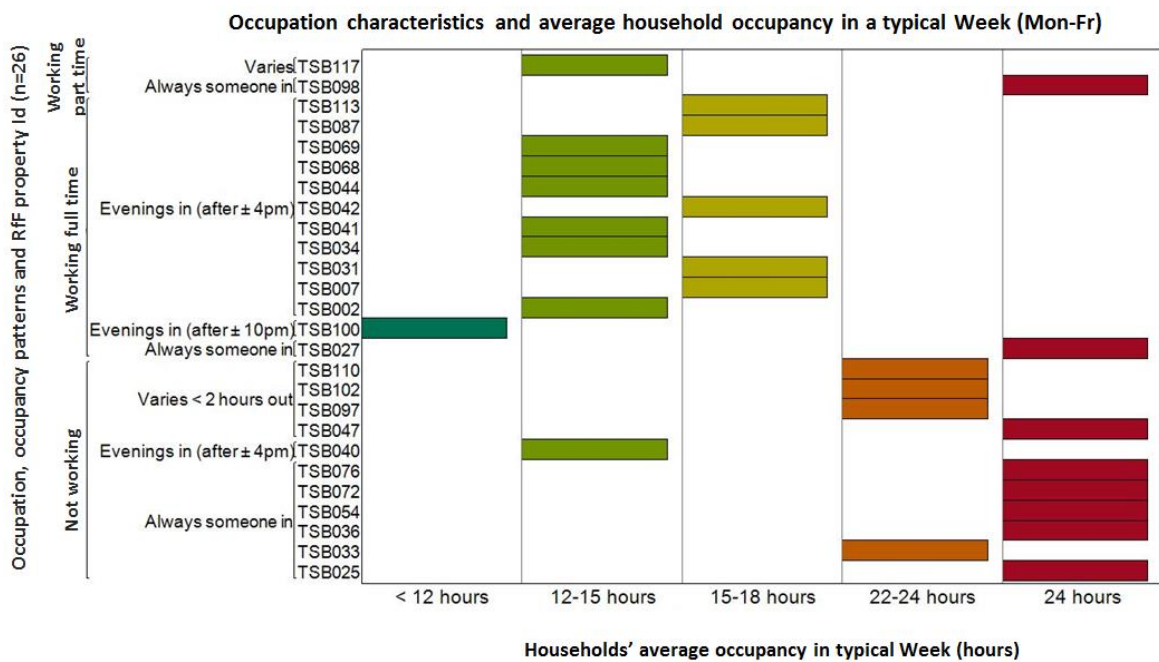


Figure 78: Household's average occupancy in a typical week (n=26).

Two other groups with adults working either full or part time and children in school make up the majority of the households (n=15) in the sample. In these groups the time of occupancy varies between 12 hours and 18 hours, mostly in the evenings (approx. after 4pm), when the whole family is at home. There is only one case (TSB100) in this group in which occupants spend fewer than 12 hours in the evenings at home. In cases TSB098 and

TSB027, even though the couple is working full or part time, there is always someone in the house looking after younger children.

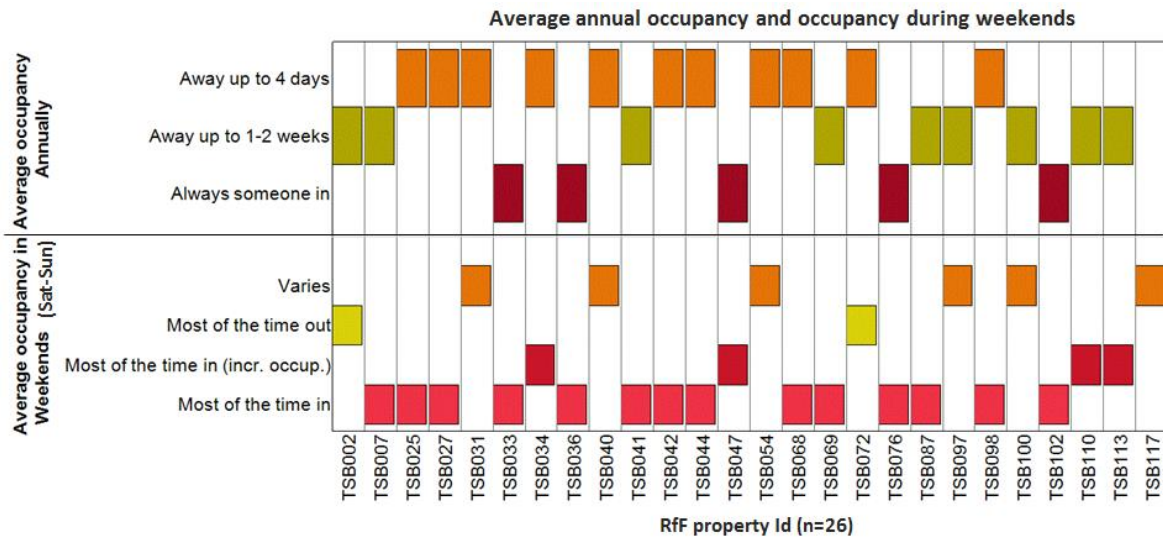


Figure 79: Households' average occupancy annually and during the weekends (Sat-Sun) (n=26).

On the weekends (Saturdays and Sundays) the occupants in the majority of the households (n=18) stay in the house for most of the day. In this group of high occupancy there are also four cases (TSB034, 047, 110 and 113) in which the occupancy during the weekends is increased by visiting family members and friends. In only two cases (TSB022 and TSB072) the properties are most of the time vacant on the weekends; in the rest of the cases (n=6) the time of occupancy varies during the day due to working schedules and family activities.

The annual occupancy of the households in the sample has shown that in a very few cases (n=5) there is always someone in the property throughout the year. In most of the properties (n=11) occupants are out for short holidays of up to four days; in nine of the 26 cases occupants are away for longer periods of 1 to 2 weeks. For this latter group heating controls and energy usage are cross checked with the physical monitoring data.

As regards the occupied space two main groups of rooms in which households' activities take place – day zone and night zone rooms – emerged from the sample. These are the rooms that are heated and ventilated in a typical week during the UK heating and cooling seasons. The group of day zone space includes the living spaces (kitchen, living room and dining room) on the ground floor where occupants carry out most of their activities on a typical day during the week. In Figure 80, the level of occupancy indicates the time spent in the room when the household is occupied as discussed in previously in Figure 78.

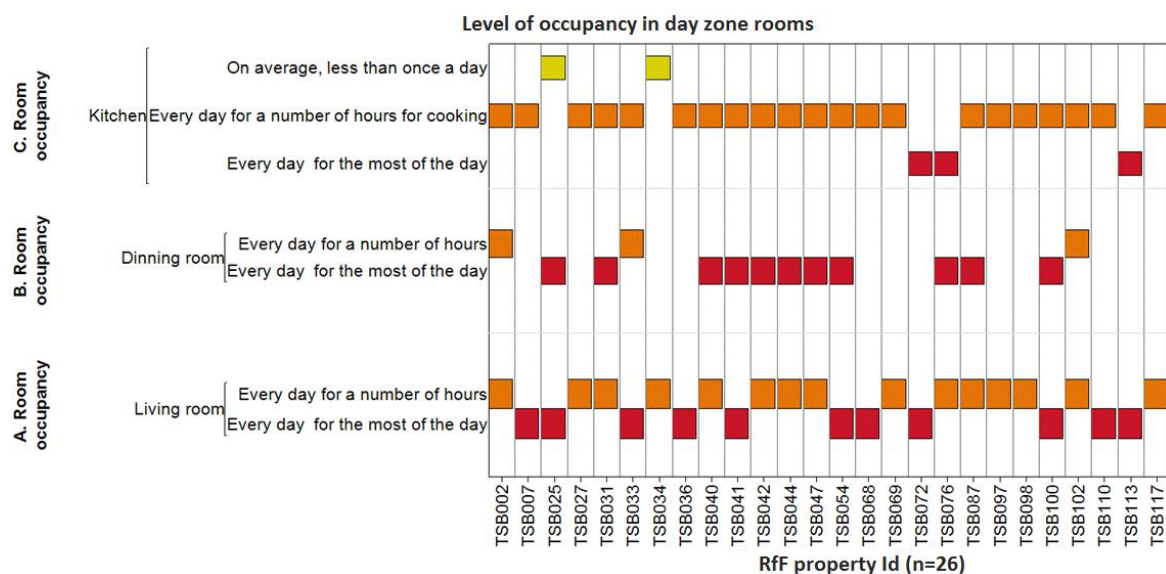


Figure 80: The level of household occupancy in the day zone rooms (n=26).

In the majority of the properties (n=21) the kitchen is occupied for a couple of hours in the mornings and evenings (after 4:00 pm) for cooking, whereas in only two cases the space is occupied for less than once a day (Figure 81). In three cases the kitchen is open plan with the living room and dining room; for these cases the open plan space is the core of the house and occupied for the most of the day. In the majority of the properties with a dining room (11 of the 14 cases) the space is highly occupied for the most of the day. The living room in most of the cases (n=15) has a medium level of occupancy for only a number of hours. In eight cases (n=8, TSB002, 027, 034, 069, 097, 098, 102 and 117) the time of occupancy ranges for the day zone rooms, with medium occupancy in all of them.

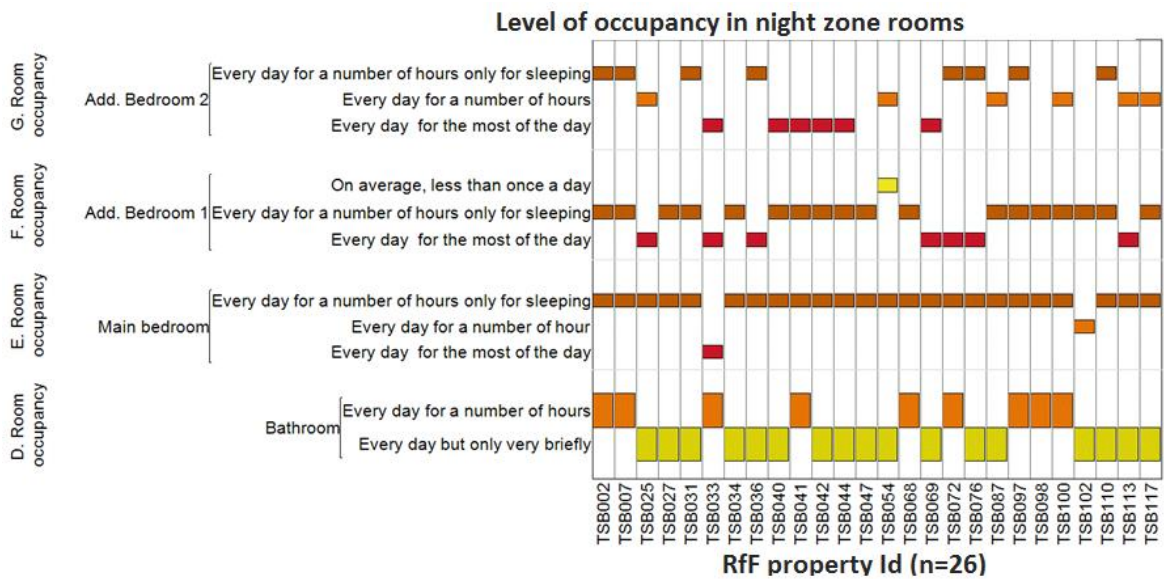


Figure 81: The level of households' occupancy in the night zone rooms (n=26).

The night zone space includes bedrooms and bathrooms located mostly on the second floor. In only a few cases, as shown in Figure 81, these rooms are also found on the ground floor. As regards the bedrooms in this group two main activity patterns were found: one in which the majority (n=24) of the occupants use the space only for sleep at night (in only two cases the room is used also as working space), and another where children, especially of age fourteen and above spend most of their time after school in their room. Higher occupancy in the bathroom was also found in the cases of families with children that follow a bath routine with young children every evening.

Summary and discussion

This chapter tackled the first two sections of the analysis objectives⁴³, focussing on the pre and post-refurbishment characteristics of buildings and occupants in the RfF sample. Technical factors were evaluated in the 'as designed' and 'as installed' stage. Non-technical socio-demographic, economic and occupancy factors have looked at the

⁴³ *The three sections of analysis objectives were presented in Chapter 5, Table 9, p.164.*

individual occupants of the household as a whole to draw out the ‘as occupied’ post-refurbishment households’ characteristics.

The technical characteristics have discussed location in terms of historical value restriction of the area, of natural environment and climatic conditions and of residential density. These appear to be significant factors that affect the design choice of some measures like solar technology, type of installation in wall insulation and ventilation. For instance, building conservation restrictions in the sample have explicitly leaned to internal insulation and mixed solutions. Although in some of the cases in the sample such factors have been a determinant that ruled out the design choice of low-carbon technologies, in other instances, like in the case of rural areas and mechanical ventilation systems, the design choice was found to be driven more by the need to comply with the given RfF package of low-carbon measures than to integrate design into locations’ environment.

Regardless of the building’s construction type, external insulation solutions were found to be the most common approach in the semi-detached and end-terrace properties. The thermal imaging comparisons in the properties insulated externally have shown that construction failures are minimised and overall buildings’ fabric has fewer thermal bridging defects. Insights from the airtightness and thermal imaging tests point out construction and installation failures. This highlights that deep refurbishment to high performance standards cannot be achieved by simply having only high standards of design and a number of high performance innovative measures; rather, high level implementation of standards in the construction and installation stages are necessary. From the analysis of these technical characteristics the study demonstrates that one package of low-carbon innovative technical solutions or ‘mass’ design choices cannot fit all cases, regardless of how similar they are. They may shape the broad design guidelines for deep refurbishments and to a great extent facilitate low-carbon policy implementation; however, every single

building, even from only a technical perspective, has its own attributes that need to be particularly considered in both design and installation stages.

The low-carbon technology of the building fabric, systems and measures affects occupants' controls interaction, not only in terms of products' actual 'scripted'/prefigured factors 'as designed', but also to a great extent by the way these were installed and performed in use. At this stage of the analysis systems and measures in the sample were assessed from a technical perspective as products, whether their designed interaction with the user was initially 'scripted' as a measure for either direct or indirect use and designed for passive or active users. With the exception of the gas boiler, all direct heating controls on the primary heating unit are designed for passive users and involve only indirect operation via conventional or intelligent controls. Passive design measures like thermal blinds as well as active design including both conventional and intelligent of heating system controls were explicitly designed for active users. There are only a few cases where controls on the heating source like TRVs and MVHR air valve were deliberately designed and installed for passive users. Hot water systems and controls were designed similarly for space heating; whereas solar thermal system controls designed for passive users. Windows and doors systems for natural ventilation as well as the mechanical control panels and boost button, the MVHR air valve controls and fan ON/OFF switch were all designed for active users. Measures like doors' undercut gap and combined one switch fan and light controls were designed to allow no interaction with the user, whereas openings' operation has considered passive users. It can be said that overall at the design stage, most of the control systems and measures are designed for active users with just a few scripted constraints.

The non-technical socio-demographic and socio-economic determinants related to occupants' personal aspects in the RfF households stemmed from occupants'

characteristics and background. Correlations were found among family composition, occupants' ages, number of occupants and floor area per capita. The majority of the social housing households are families between 30 and 50 years of age, with children, and mostly of a white cultural background. The vast majority of the cases in the sample represent the typical social household that is in middle to low economic levels and paying for their own energy bills, whereas their qualifications and educational background are only in a very few cases related to the building and construction sector. A high number of cases where one or more occupants have health issues or conditions were found in the sample. Two groups emerged from the sample. In one group, occupants' health is related to the indoor comfort levels and the ways health affects their interaction and practices in heating and cooling. In the other group, the ways health issues affect occupancy and occupants interact with the indoor space. Both groups are analysed in the following chapter, focussing on correlations between health and occupants' interaction and energy use prior to and subsequent to refurbishment. Although the effect of micro-factors on the indoor comfort and CO₂ levels cannot be discussed at this primary stage of analysis, it was found that a small number of occupants smoke indoors, with the vast majority smoking outdoors, and a great number of households have pets that live indoors. Both factors need to be examined in relation to other variables and buildings' physical data to evaluate the extent to which they affect users' interaction with ventilation measures.

In terms of the occupancy background it appears that the vast majority of the social tenants were living in the property before the RfF refurbishment interventions; and more than half of them lived in the property during the works. Their post-occupancy time may vary in the sample; however, it is important for the study's analysis that most of the households have experience of a minimum of two heating and cooling months in the RfF property. These aspects are seen in relation to their post-occupancy experience in the refurbished property

in terms of training provided, understanding of measures and interaction with heating and ventilation system controls.

A correlation was found between the occupation type and the time during which the house is occupied by one or more users during the day in a typical week. There was high occupancy in households (24 hours) in which one or more occupants of the household was not working and medium occupancy in the evenings in the households that were working full or part time and where children were in school. In the day zones, the dining room was found to be a highly occupied room for most of the day whereas a medium level of occupancy was found for only a certain number of hours in the living room. The vast majority of night zone rooms are used only for night hours sleeping and for teenage children after school hours. High occupancy was found for the vast majority of the cases during the weekends, while the RfF properties are vacant (not occupied), mostly only for long weekends or for a maximum of a couple of weeks. The number of heated rooms was found to be proportional to the floor area of the properties and consequently for most of the cases to the number of the occupants in the household. Correlation between these factors, occupancy and physical data, is discussed in Chapter 8.

This section has summarised the most significant technical and non-technical factors that emerged from the sample. These factors are examined in the following chapter in relation to interaction variables to identify their type and frequency and examine the cause and effect of these interactions.

Chapter 8: Interaction drivers and in-use evaluation

In this second chapter of analysis socio-technical determinants explore the factors in which user(s) interact with the low-carbon measures installed. The energy evaluation, actual and estimated, was used to investigate factors related to households' energy consumption and their impact on the actual energy in use. Key factors affecting past-experience and occupants' heating and ventilation control practices were analysed together with the post-refurbishment experience to understand behaviour changes in energy use. Interrelations between technical and non-technical determinants or aspects related to the RfF competition process related to occupants' heating and ventilation practices are discussed. Other factors presented here are those determined by occupants' perceptions of the property and new innovative measures installed as well as controls' interaction, comfort related determinants and knowledge pre and post-refurbishment.

8.1 Evaluation of energy in use

From the validation of the physical monitoring, as discussed in Chapter 6, electricity and gas data was available for fifteen cases (out of 26) and eleven cases (out of 16) respectively. The modelled building performance estimated using SAP and PHPP modelling approaches in the RfF documentation was compared against the actual pre and post-refurbishment performance.

The comparison shows a significant gap between the estimated and actual electricity consumption. In almost all the cases (14 of 15), with TSB076 being the exception, the predicted consumption was lower than the actual values (Figure 82).

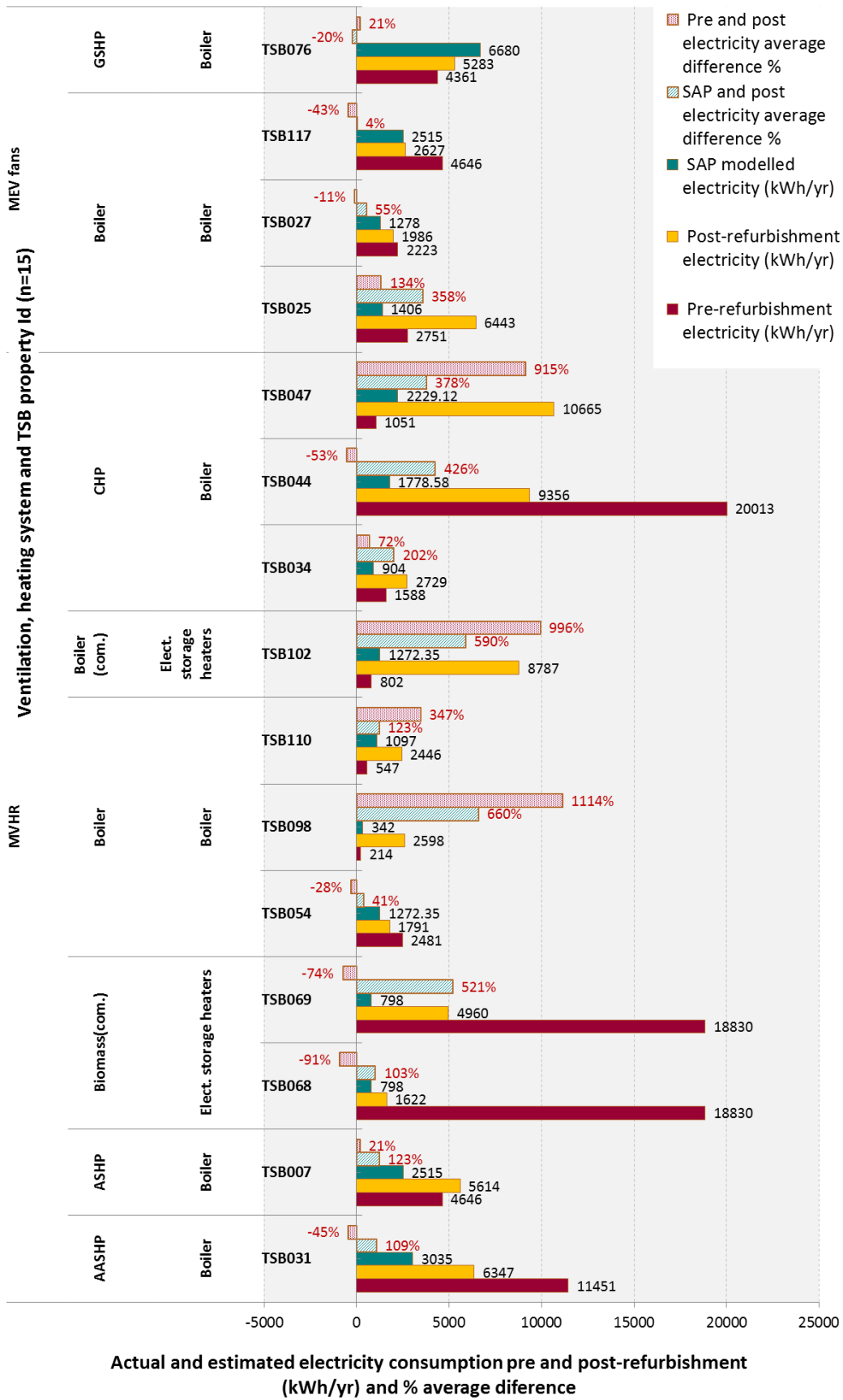


Figure 82: Comparison of actual and estimated/modelled electricity consumption pre and post-refurbishment in relation to the heating and ventilation system (n=14).

There was fuel switching in six of fifteen cases from previous gas boiler and electric storage heating systems to low-carbon systems. In eight out of fifteen cases there was a considerably high increase in electricity, with most properties (6 out of 8) often exceeding significantly both previous consumption and SAP estimated targets. In seven of these properties the excess of electric consumption was despite that gas continued to be their main heating fuel post-refurbishment; and in two of these cases (TSB025 and 047) regardless of the PVs estimates generating 29.7% kWh and 16.4% kWh of their annual electricity consumption. Even for the cases with the smallest onsite photovoltaic panel array (1kWp) the estimated electric production it would have been an input of 9.1% to 44.5% kWh/year of their actual consumption. As a consequence the performance gap between the estimated and actual electricity appears as a larger difference when the PVs forecasted input is compared to the actual electricity consumption (Figure 83). However, it is difficult to explain electricity consumption variations as result of the photovoltaic systems installed given that data from the PVs actual generation has not been provided and only the estimates allow comparisons.

In some cases like TSB007 and 076, the electricity increase was explained by the shift from gas boiler to ASHP heating system and also in the former case by the failure of the MVHR performing to best practice standards due to installation faults⁴⁴. Or like for instance in case TSB102 despite the expected electricity reductions switching from electricity to gas boiler occupants mixed energy behaviour post-refurbishment using frequently additional electric heaters during cold months had opposite results. And other factors like the extra number of occupants⁴⁵ living temporarily in the property after works

44 Failures in MVHR design and system pressure losses can lead to inefficient operation of the fans that can double energy consumption.

45 At the time of the RfF competition the recession in the UK was severe; as a result there were cases (n=4) in the study's sample in which adult 'children' between 18 and 50 years of age had returned to live temporarily with their parents in the post-refurbished RfF property.

(e.g. TSB076, 034 and 102) need to be considered as they often affected a household's energy efficiency behaviour and routinised practices.

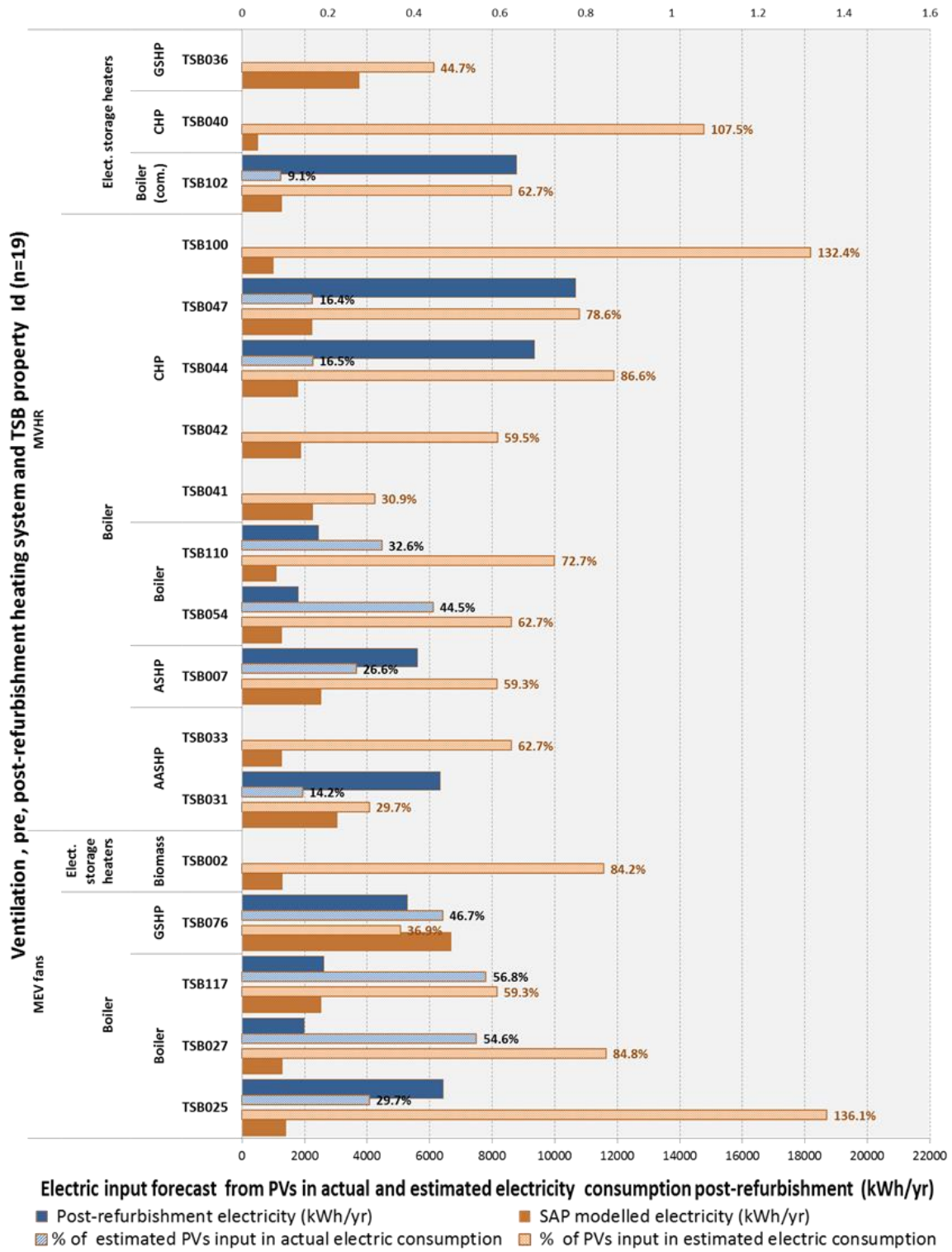


Figure 83: Comparison of estimated electricity generation from PVs and modelled/ actual post-refurbishment electricity consumption in relation to ventilation and pre, post-refurbishment heating system (n=19).

In cases with similar floor area per capita no significant variations were found between the MVHR and MEV systems to solely account for electricity increase. Lacking of MVHR electric loads data the study was not able to identify the extent installation and performance issues, as emerged from the sample, have affected the total electrical consumption for each property. Decrease of electrical consumption in the post-refurbished house compared to the previous situation was found in seven of fifteen cases. Reductions in four of seven cases of the electrical consumption range from 11% to 53%, in systems using the same heating fuel pre and post-refurbishment (gas to gas); and even lower to 91% to 45% in cases with new low-carbon heating systems installed post-refurbishment.

In cases with gas as a heating fuel there was a significant drop of the gas consumption in the post-refurbishment stage, fluctuating from 42% to 90% (Figure 84). For the cases with the same heating fuel pre and post-refurbishment this drop indicates the large improvement in their heating system efficiency. Although the gap between the estimated/modelled gas consumption is generally smaller, in six of eleven cases predicted is higher than actual consumption. Nevertheless, the figures for both gas and electricity indicate a failure of the modelling tools (SAP) to accurately estimate post-refurbishment building and systems performance.

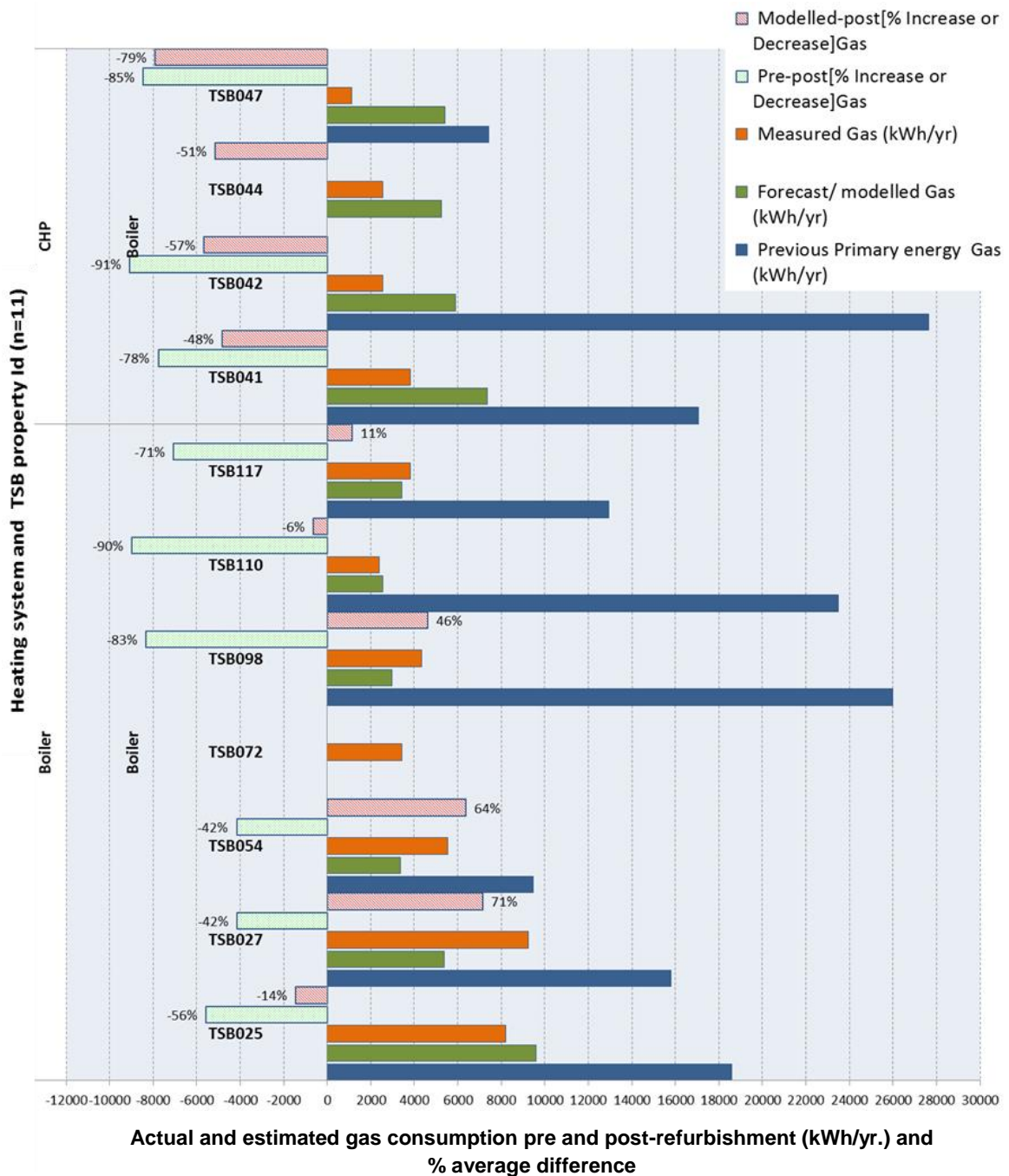


Figure 84: Comparison of actual and estimated/modelled gas consumption pre and post-refurbishment.

From the energy performance line calculation⁴⁶ in cases TSB025, 110, 027 and 054, although their gas consumption was decreased, the R^2 value was found at around 0.6 and below, indicating a poor correlation between energy consumption and degree days; this also indicates either a rather poor heating control or the need for a larger quantity of data

⁴⁶ A base temperature of 10°C is recommended for a thermally well insulated building with large internal gains (<http://www.eci.ox.ac.uk/research/energy/degreedays.php>).

available for accurate analysis. In this respect malfunction of the system could also be a reason for poor performance line results. As Figure 208 shows (Appendix 23), significant gas peaks do not follow indoor temperatures (e.g. TSB041, 117 and 110), conforming to occupants' mentions of problems with the system. Only in one case (TSB072) was the R^2 value found to be above 0.75, which indicates a reasonable correlation between energy consumption and degree days (Appendix 24, Figure 209-Figure 213). In these latter cases no correlation was found between occupants' level and type of heating controls and their practices to warm up with the building's heating performance.

8.2 Occupants' past-experience interaction

This section introduces key socio-technical factors defining occupants' past-experience in the previous property or in the same property before low-carbon refurbishment works. This includes occupants' perceptions and satisfaction with the previous building environment. Previous heating control practices and comfort levels are established in this section. Occupants' overall opinion of the previous property, whether this was the existing or a new house, has been an important factor in the study's analysis to understand post-experience energy behaviour changes from living in the RfF property.

The occupants in the sample were asked to describe what it was like to live in the previous environment, drawing attention to the positive and negative aspects. Occupants' opinions were examined within the two groups of background occupancy: those living in the property before and those who moved in after. However, no major differences were found between the two groups at this stage of the analysis. Their past-experience was found to be largely negative in both groups, with the majority of them feeling generally negative or very negative (10 out of 14 and 8 out of 12) and only in a few cases feeling generally positive or very positive (n=3 and 2 respectively, Figure 85). For only a small number of

households (n=3) the previous building environment had both negative and positive aspects affecting occupants' living experience in the property.

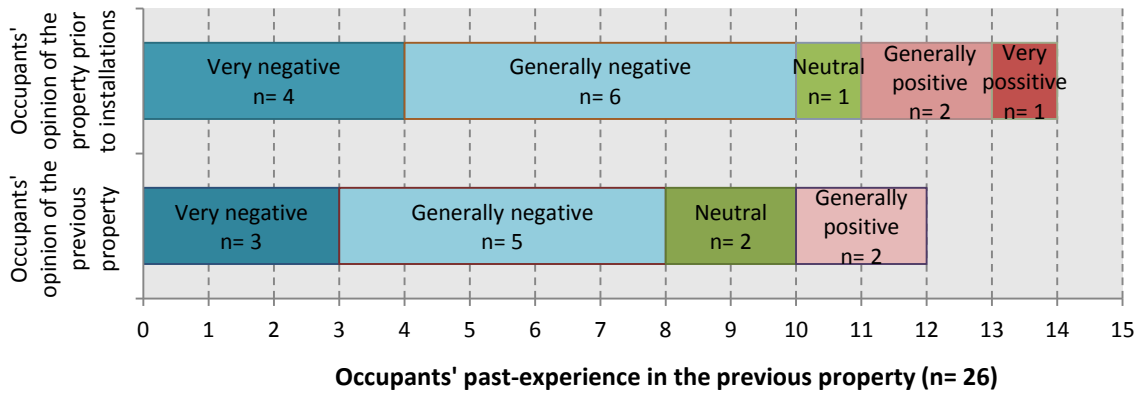


Figure 85: Occupants' opinions of the previous property and RfF property before refurbishment works (n=26).

The occupants were also asked to explain the factors affecting their opinions and describe their level of satisfaction with the previous building environment in terms of draughts, damp, smells and internal air quality as well as of noise, security, overall design and size. Their responses were given using a satisfaction scale ranging from 1 (very unsatisfactory) to 5 (very satisfactory). Figure 86 shows that most of the occupants were unsatisfied with buildings' overall previous condition (n=17 properties).

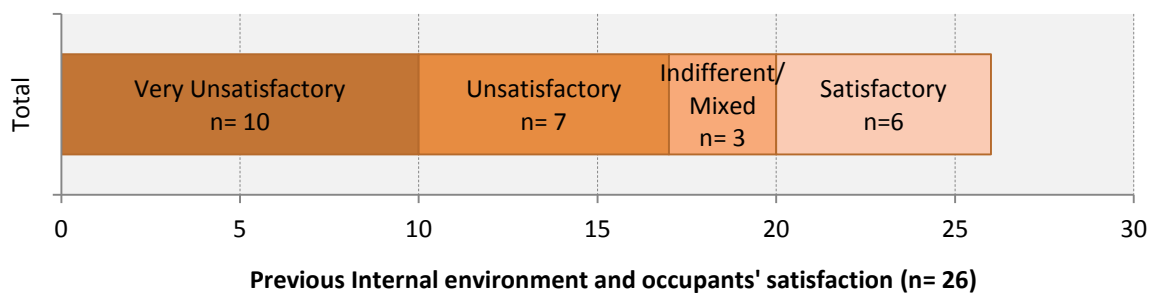


Figure 86: Past -experience: Occupants' satisfaction with previous building environment.

Four main factors emerged from the interviews as negatively affecting occupants' overall past-experience in both groups. As Table 18 shows, these are related explicitly to the building and its size, condition, controls and context. Only in a few cases (n=5) were

occupants satisfied with their past-experience in the previous building environment (Figure 87). These were mainly the cases where intervention of Decent Home standards was undertaken for the building fabric, before the RfF project took place, involving merely roof insulation and window replacement.

Factors	Factor description
Building condition	Poor condition of the building fabric, temperature variation affecting occupants' comfort levels
Building size	Need for more space, different layout to cover their family needs
Building controls	Lack of heating controls
Building context	Location, neighbourhood, noise and security issues

Table 18: Factors negatively affecting occupants' past-experience living in the previous property.

The poor and cold building environment has been the main negative factor in the majority of cases, with most of the occupants mainly unsatisfied due to the extensive draughts, damp, smells from mould and overall very poor air quality (Appendix 25, Figure 214). Occupants have described poor indoor conditions with extreme temperature variations between rooms and floors and significant heat losses due to the poor condition of the building fabric, such as openings' poor quality and uninsulated roofs and walls. There were a few cases in which more than one factor contributed to occupants' negative past-experience in the building. The poor indoor environment and air quality also had a significant impact on the occupants' health conditions (like asthma, chest infections, rheumatism, etc. – Chapter 7, Figure 73: p.258).

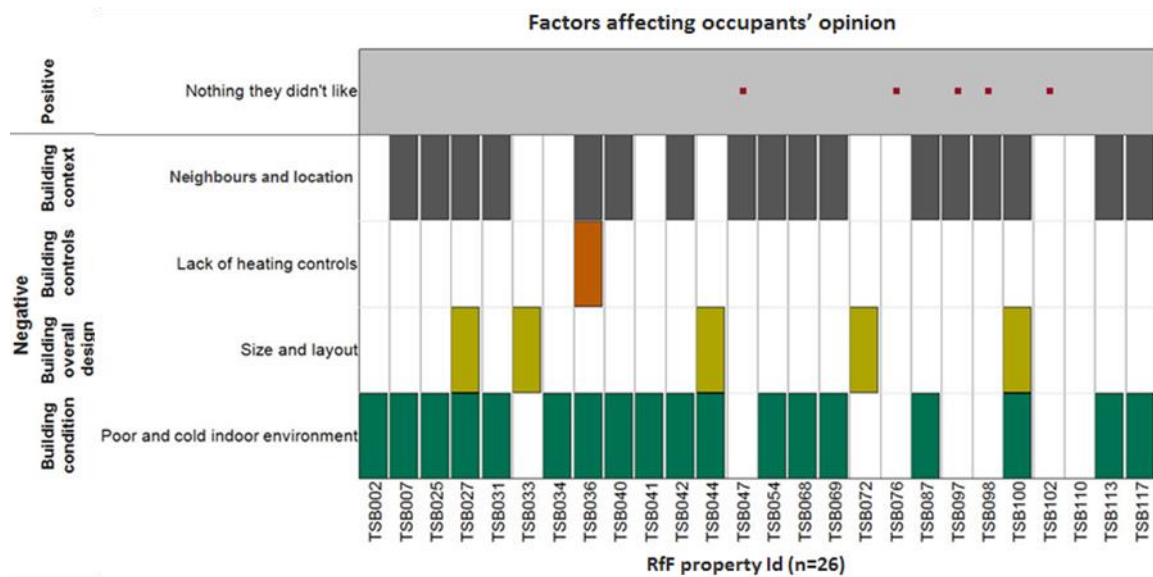


Figure 87: Occupants' negative and positive past-experience living in the previous building environment.

Occupants' satisfaction regarding the overall design of the previous property in most of the cases (n=14) was found to be indifferent or mixed (Appendix 25, Figure 214). Only in a few cases were the size and layout found to be related negatively to occupants' health conditions in terms of interacting with space. Those were mainly the cases of occupants with mobility and disability issues and the households where the size of the previous house was not suitable for their needs, especially in the cases of families with increasing numbers of children. For almost half of the cases, security aspects and noise of the deprived neighbourhood or neighbours in the previous building context have been an issue. It is important to note that only in one case in the sample did the occupants consider the lack of heating controls negative.

The level of awareness and occupants' energy efficiency perceptions before moving into the RfF property were found to be rather confounded in the sample. In the majority of the cases (n=20), although occupants indicate having a 'green lifestyle' and being conscious of using energy, their 'sayings' show that energy behaviour mainly consisted of a mix of contradictory practices. In most of the cases occupants were found to understand their energy-saving behaviour and lifestyle in terms of practices like recycling without taking

any other energy conservation action (9 out of 20 cases) (Figure 88). Others, although they had good control of the heating systems, always had the heating ON and the windows open due to their sleeping habits or smoking indoors. In addition, there were those who, although they were using energy conservation practices to regulate their thermal comfort, always left the lights and television ON.

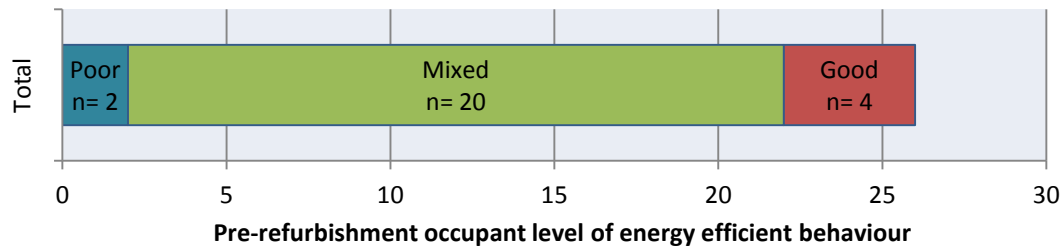


Figure 88: The level of energy efficient behaviour before moving in the RfF property (n=26).

In a couple of cases occupants' poor energy-saving behaviour is due to the lack of understanding and interest in energy conservation matters. Only in a small number (n=4) of cases did occupants employ different energy-saving practices due to their personal energy-saving perceptions and lifestyle or in order to keep their household's energy costs low.

In the following sections occupants' past-experience in energy saving and their level of awareness of energy efficient behaviour are discussed in comparison to their post-refurbishment experience in the RfF property.

8.2.1 Previous heating systems' controls and comfort adaptations

Occupants' past-experience with heating controls is discussed in terms of understanding, ease of use and actual control of the previous heating systems. Occupants were found to have interacted with two types of heating systems in the previous buildings: gas central heating, including either a combi or condensing boiler controlled by a thermostat and

programmer (n=21), and electric heating with storage heaters and an electric fireplace (n=5) (Figure 89).

Occupants have self-report a *good* or *excellent* understanding of the previous heating controls in central gas systems (n=13) and *full control* of the heating measures (n=12). This is particularly true of occupants who have found the controls *easy to use* by setting the timer in the programmer (n=5) to their occupancy preferences or using the thermostat as well (n=7). In other cases (n=7), although occupants find gas system controls *easy to use*, the lack of knowledge and occupants' *mixed* understanding of operating the heating controls often appears as a constraint. In these cases their control strategy for controlling the system is turning it manually ON/OFF from the thermostat. Other heating controls like radiator TRVs, when were provided, usually stayed turned to a higher level without any particular interaction by the users. The *poor* and *mixed* understanding of the controls (n=9), despite how occupants found the use (*easy to use* and *indifferent*) in their responses, results in *poor* and *mixed* control.

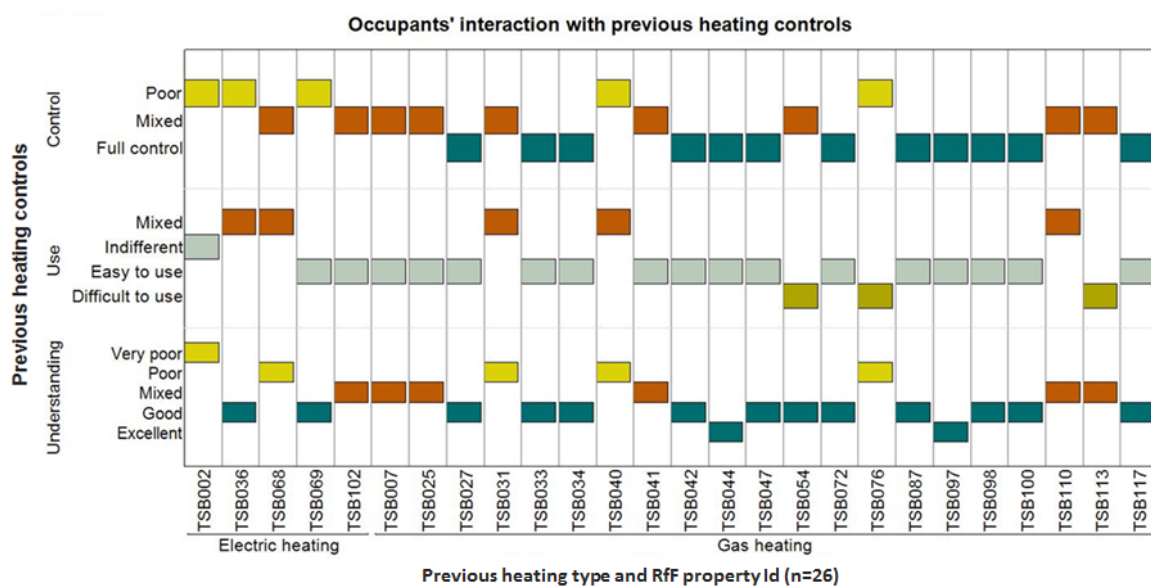


Figure 89: Past-experience: Previous heating systems and occupants' controls (n=26 properties).

In households with electric heating systems occupants had either *poor* or *mixed* control over the system. This is mainly due to the storage heaters' constraints on storing heat during the night and keeping the house heated in the daytime, which differed from households' occupancy patterns, as well as the very high energy cost to run the heating system. Regardless of occupants' level of understanding and the ease of using these heating controls, in almost half of the cases (n=14) the poor physical conditions of the previous building fabric and the high heating costs constrained occupants' *full control* of the system controls (electrical or gas).

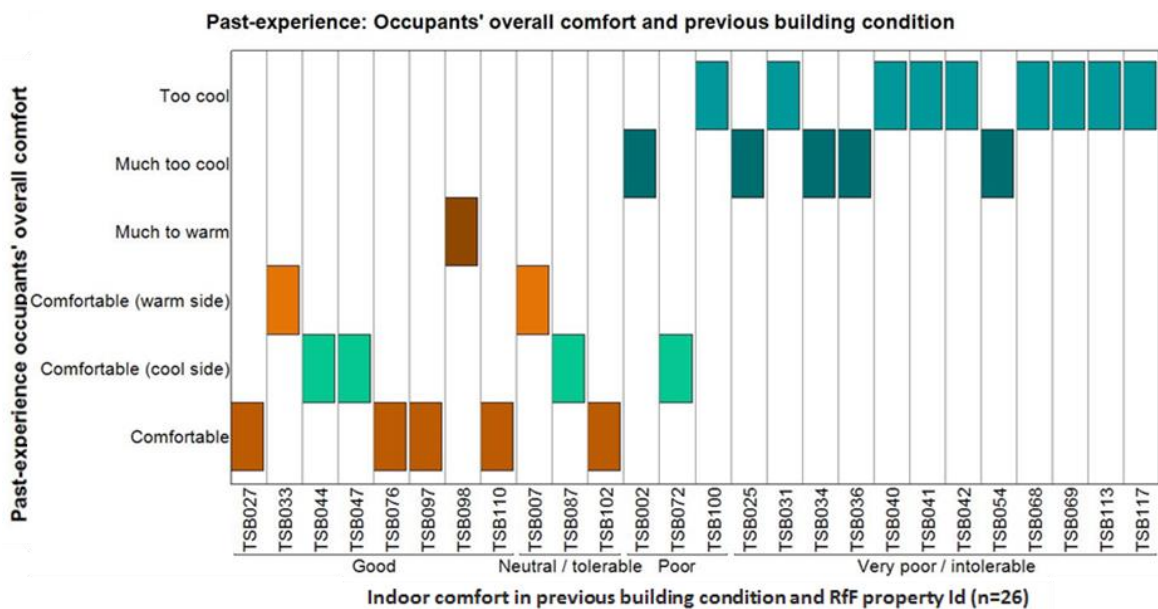


Figure 90: Past-experience: Occupants' comfort levels and previous building environment (n=26).

When occupants' comfort levels were significantly affected by the extreme temperatures of the indoor environment, conditions were described in the most of the cases (n=15) as *poor* or *very poor/intolerable* (Figure 90 above). During the cold months occupants' comfort levels were found to vary between *comfortable to the cool side* and *much too cool* (n=19 properties). The main issue reported was the insufficiency of the previous fabric condition to keep the heat in and the high cost to run the heating system. Especially for the

occupants with health issues (as discussed in Chapter 7, Figure 73: p.258) the poor indoor conditions affected not only their comfort levels but also their practices to regulate it.

Different practices were found in the sample however, the most common practice to warm up was to turn the heating on (Figure 91 below). Therefore it was found that previously occupants in cold months often had the thermostat setting constantly at 25°C and sometimes even up to 30°C, especially those with young children during occupancy hours. Or in other cases due to the cost occupants would turn it on only when they had visitors. Very few are the cases where occupants were using other practices or a combination of practices like secondary heaters or adding more layers of clothes.

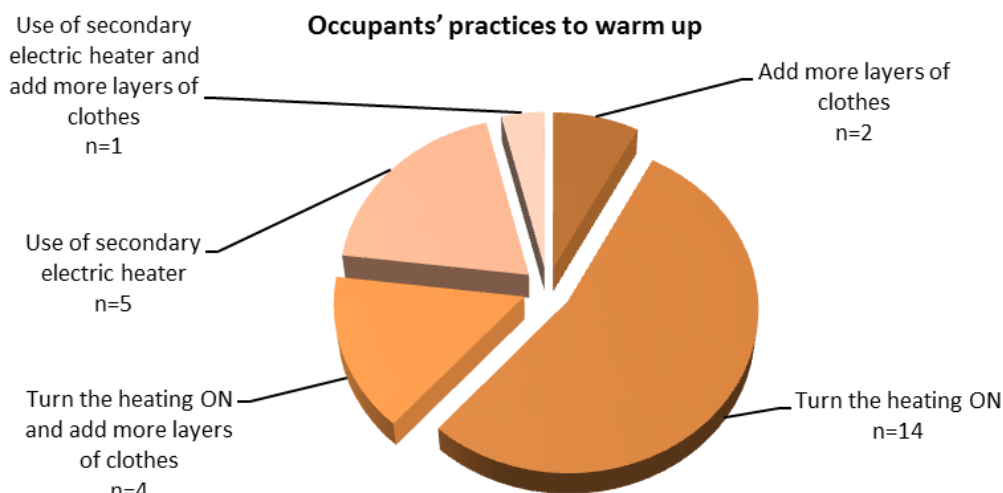


Figure 91: Past-experience: Occupants' heating practices (n=26).

As mentioned previously extreme temperature variations often existed not only between seasons (warmer and cooler months) but also between floors and rooms. Therefore occupants like in case TSB100 reported a cold indoor environment even in the warm months, whereas for other cases like TSB041 the 1st floor was overheated, requiring electric vent fans on all the time. In the warmer months occupants' most common practice to drop the indoor temperature was to open windows or doors; and only a small number was using electric ventilation fans (Figure 92 below).

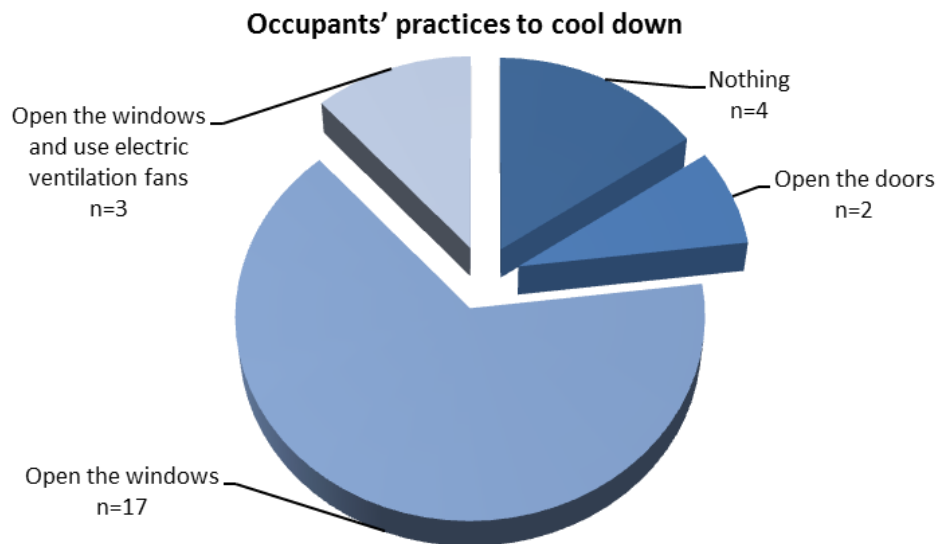


Figure 92: Past-experience: Occupants' cooling practices (n=26).

8.3 Occupants' post-experience interaction

Occupants' perceptions of the property following installation works are presented in this section. Occupants were asked to discuss their level of satisfaction and perceptions of the property post-installation in terms of the internal building environment within the two groups (living in the building before and after refurbishment works). Figure 93, shows that to a great extent occupants' level of satisfaction with properties' indoor environment has changed, suggesting that building's overall condition has clearly improved as there are no occupants reporting unsatisfactory conditions after the RfF refurbishment works.

Of the twenty cases reporting general satisfaction with the post-refurbished building environment, for fifteen it has been a significant change living in the refurbished building. For these cases occupants' satisfaction with the property is mainly determined by the past negative experience they had in the previous house. The main reason that occupants report being generally satisfied with the refurbished property is the change in terms of indoor comfort in both warmer and cooler months and the improved air quality.

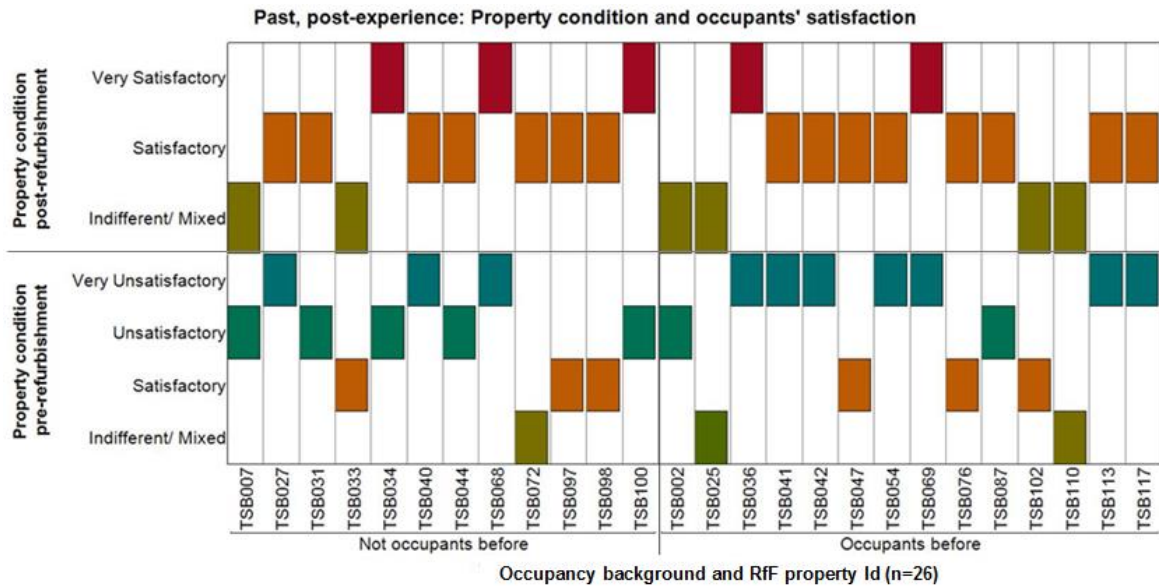


Figure 93: Occupants' satisfaction and property condition pre and post-refurbishment works.

The reduction in their bills and living in a warm environment have been significant factors for some of the households⁴⁷ (e.g. TSB040, 072, 068). There are also cases where, although occupants report being generally satisfied, they raise some issues and pending conditions regarding their satisfaction levels. Therefore, they are still expecting all the innovative systems installed to work as are designed to (e.g. TSB044, 076), or in other cases (e.g. TSB041) they feel more as if the property was redecorated rather than leading to benefits from the measures as although a year or more living in they are still expecting to see how much energy they will actually save. Regarding their satisfaction level, other positive factors reported were that their property was 'modernised' and they prefer it in terms of size, building features like openings and new appliances (e.g. TSB047, 040, 072, 076, 100); fewer (e.g. TSB027) reported that this was because of their personal interest in the technology installed in their property.

However, this is not the case for the four properties (TSB097, 098, 047 and 076) where the satisfaction level was unchanged from before. One case was also found in both groups

⁴⁷ These are the reported occupants' perceptions of their post-experience in the refurbished building fabric until the day of the interview.

(occupants before and after) where occupants who gave the previous building a *satisfactory* rating have *indifferent/mixed* feelings about the refurbished building, having both negative and positive opinions (TSB033 and 102). The negative aspects in occupants' opinions in the first case were design issues related to disability features as they are not all incorporated in the low-carbon design, as well as their energy bills increasing. In the second case the occupants felt that except for the improved indoor comfort there was no positive change in the property as their energy costs increased and the heating system (wood pellet) has significantly affected their daily routine. In all six cases in which occupants indicate an *indifferent/mixed* satisfaction level there are four main negative factors reported that are related to energy (Table 19).

Factors	Factor description
Construction and installation faults	Installation failures of the openings (e.g. draughts from the front entrance)
Design	Lack of storage space (e.g. previous storage space now used for the low-carbon system equipment)
System and measures	Heating system controls (not being able to have full control over the system) and triple glazing opening operation due to their weight
Increased energy bills	Compared to their past-experience in the previous property or before RfF works

Table 19: Factors negatively affecting occupants' post-experience living in the RfF property.

These negative aspects are explained by the fact that although the poor buildings' fabric before intervention works has been significantly improved, there are still cases (n=6, indifferent/mixed level of satisfaction) reporting draughts due to failures of opening installation or uninsulated spaces like the porch; similarly, there are moisture issues from the wet and boiler rooms (n=1, unsatisfactory) (Appendix 25, Figure 213). Noise issues reported in the post-refurbishment building are explained by the lack of internal insulation in the party walls as observed in the study's walkthrough. The lack of storage space has

been the main design issue in most of the properties (n=15). The increased equipment of the low-carbon measures' equipment resulted in the loss of a significant amount of storage space. The fact that the occupants living in properties before or during the installation works had no participation or involvement in the design stage has not helped to improve issues like these. Thus, of the fourteen households that were living in the property before refurbishment, occupants were asked only about minor design issues like aesthetics (e.g. the floor material and carpet colour), but not about any technical or space design aspects that involved interaction (Figure 94). In most of the cases in the sample, social occupants had a long-term tenancy in the specific properties before the RfF works, as discussed in Chapter 7, Figure 76: p.261.

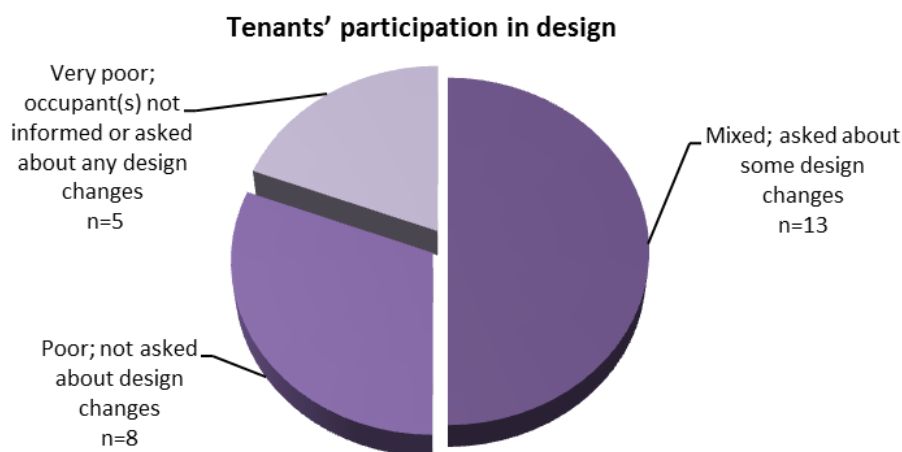


Figure 94: Occupants' participation in the design (n=26).

The design decisions may typically be the subject of the social landlords; however in these cases social tenants were familiar with and aware of the problems in the building, which could be a good step to having more substantial participation considering their different needs and expectations of the retrofit programme. In any case providing design solutions for more storage space is clearly not just a household's individual need but more of a basic architectural design value. Negative factors reported by many households like aesthetics (e.g. type of cladding or colour of window frame) of the refurbished building have not

been taken into consideration in the study as they are not related to their energy interaction with the building.

One of the main factors affecting households' overall satisfaction living in the RfF property was the refurbishment process itself and issues related to it like duration, disruption of the works, etc. Figure 95 shows that the majority of households (n=20) overall were supportive of the RfF refurbishment process and the change of their perception from supporting the process to being satisfied with it. They were generally feeling very lucky to have been selected to have their property improved or move into an 'eco-house'. Some of them found it appealing to be part of an energy 'experiment' that will contribute to the environment, save them money and allow them to interact with innovative technologies. The negative responses are of those occupants who, although they were feeling very excited for the whole RfF project, changed opinions after the negative factors experienced during the process. Of the twenty households that initially were generally positive about the RfF refurbishment process, sixteen had mixed (negative and positive) or poor (n=3) feelings about the process.

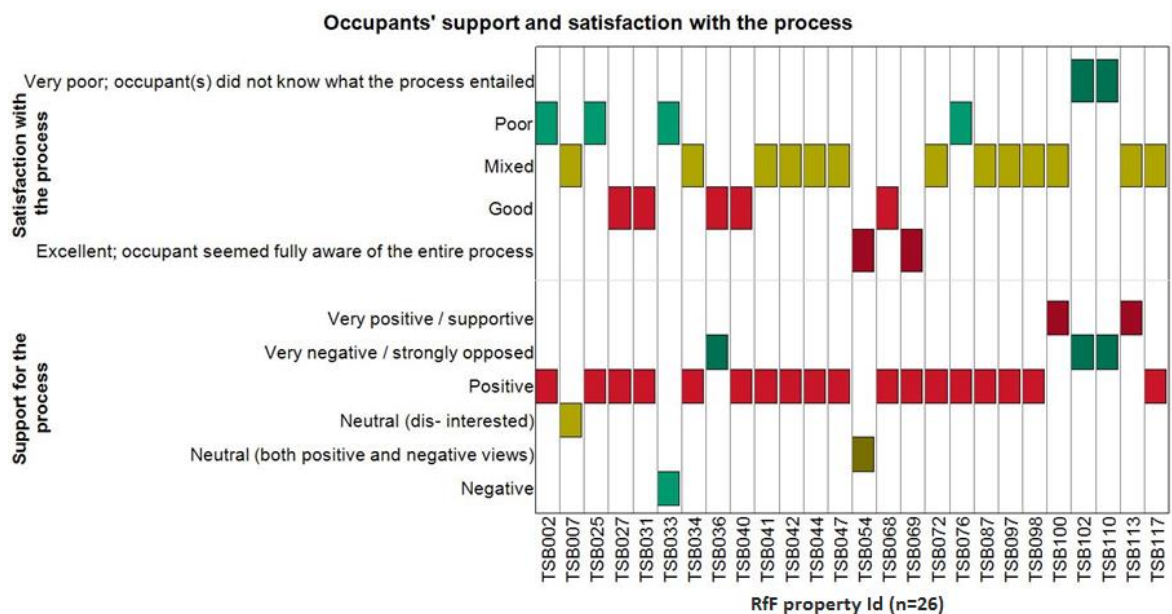


Figure 95: Post-experience: Occupants' support and satisfaction with the refurbishment process

One of the main issues that emerged was that in some properties systems and measures installed were not working ‘as designed’ or things that were included in the design proposal had not been installed nor done properly (e.g. wall finishes). In most of the cases (n=16) occupants reported a ‘snagging’ list of works that often had been rather delayed or not accomplished as of the day of the interview; only in four out 26 were all the improvements built ‘as designed’.

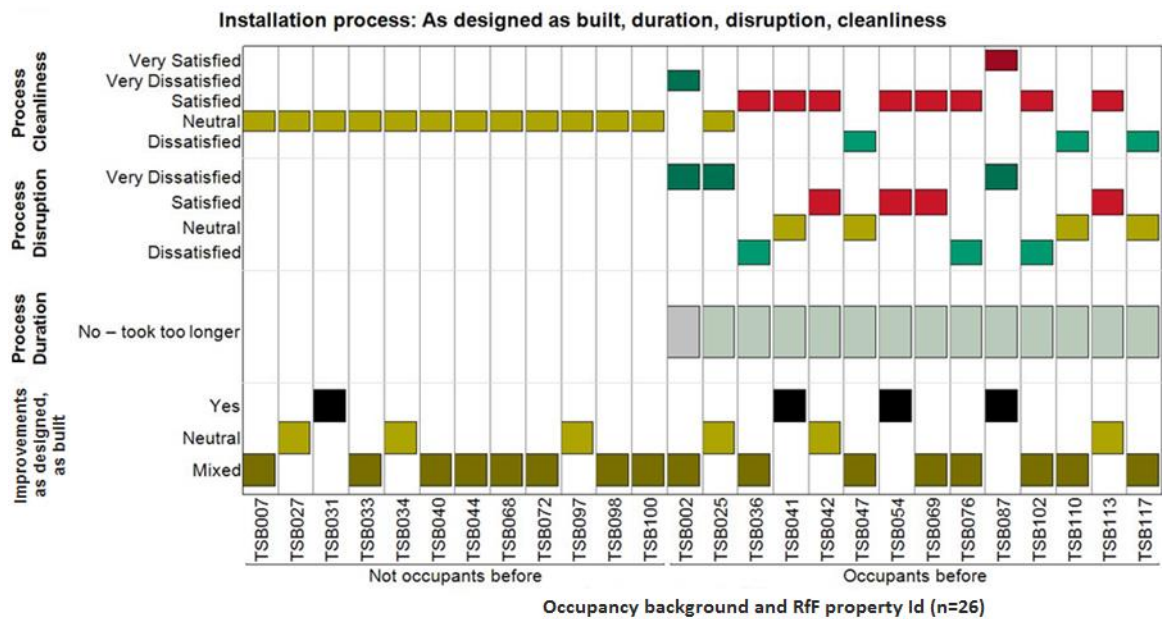


Figure 96: Post-experience: Factors affecting occupants’ satisfaction with the refurbishment process.

For the households living in the property or relocated during works (n=14), the refurbishment timeline and management of the works had a significant negative impact on them. Project delay has affected in some of these cases (e.g. TSB117) the quality or completion of works, which as reported was compromised by the rush to finish the project. In all these cases the refurbishment process took much longer than estimated. In just a couple of cases the minimum delay of the works was only up to two weeks beyond what occupants had initially been told, whereas the maximum was up to 13 months. This suggests that for refurbishment projects of this scale involving advanced technology the estimated project timeline of 3 months given in the majority of cases may have been rather

optimistic or ambitious. However, this can be explained as many projects experienced significant delays in the delivery of systems (e.g. glazing systems, insulation, etc.) and the installation due to severe weather conditions; delays were also due to poor site management, with continuing changes of project leaders and construction teams. Especially in the case of those households that had not been relocated there was mutual disruption in both the project order of works and occupants' everyday living in the construction-site . The initial intention of the RfF project for room-by-room refurbishment has not been as successful as planned in any of the cases examined. One of the factors that was difficult to plan and incorporate successfully into the refurbishment works' order was the diversity of occupants' patterns of everyday life in every household. This was largely dependent on occupants' level of engagement with the process, the project information provided and communicated before and during refurbishment, and their rapport with the project team and constructors. Thus in the six households relocated during the refurbishment works (TSB047, 041, 042, 069, 113 and 054) occupants appear either satisfied or neutral with the level of disruption as it did not directly affect their everyday life (Figure 96). On the contrary occupants' experience of living in the property during the works was found to be generally negative. The level of cleanliness that the property delivered to the occupants after work was a requirement for the project team by the RfF project which has been accomplished to a great extent.

The level of engagement with the process, the lack of information provided on measures' controls and occupants' expectations of more feedback on how they use energy have been other significant factors affecting their satisfaction with the process. A serious concern in the majority of the households was the kind of support and maintenance they would have after the two years of the project team's commitment to the RfF competition.

Figure 97 shows that there was also a slight change of occupants' level of energy efficient behaviour and awareness after works.

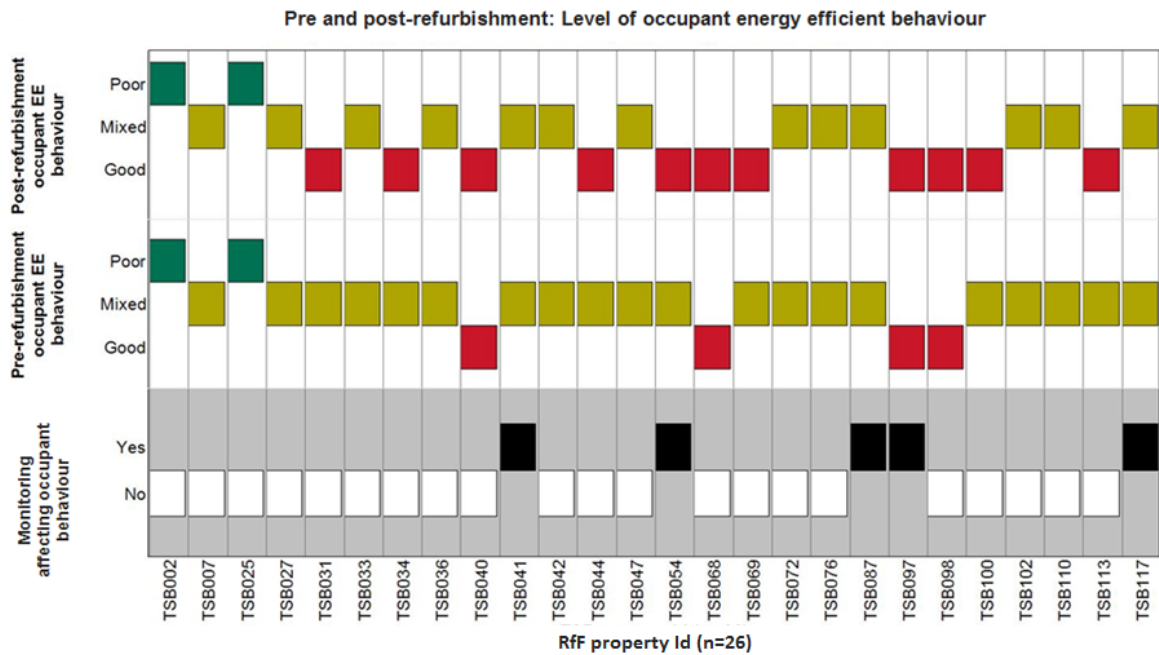


Figure 97: Pre and post-refurbishment: Occupants' changed level of awareness of energy efficiency.

Occupants that had mixed behaviour and perceptions on using energy (n=7 properties) in the post-refurbished property appear more aware and conscious of their energy controls in the post-refurbishment property. Some of them feel they have full control over the measures, which makes make them more energy aware and efficient. Others feel more eager to conserve energy because the house was designed and refurbished to help them do so, without spending too much of their time and effort. As one occupant explains:

...I think it enables you to monitor your gas and electric more because you realise the difference, whereas before I haven't really got anything to compare it to ...it makes you aware of... switching things OFF instead of having them on standby, that sort of things ...it does make you kind of conscious to see the outcome of things...and I think if we would [get] more information in regards to how this house is working and the monitoring informationit would give you more incentive....to think out how you can do better on this next time ... cause in any

other circumstancesyou wouldn't [be] given that opportunity to know by living in just a normal house ... (Occup. TSB044)

In these cases occupants report that their level of awareness was raised regardless of the monitoring equipment installed in their properties.

In all cases occupants explain that they have not changed their life routine and after a while they forgot that the equipment was installed, except for two cases (TSB054 and 097) in which the monitoring equipment has affected their interaction with windows and electrical appliances.

As discussed previously one of the main motivators for these households to participate in the RfF project was to save money on energy consumption. This factor has also affected their level of energy awareness as well as their overall satisfaction with the process and living in the post-refurbished property. A comparison of the households' energy bills pre and post-refurbishment shows that they generally decreased in most of the properties (n=21) (Figure 98). Occupants reporting a good level of energy efficient behaviour were found to have achieved a modest reduction of their bills of 20 to 50 per cent. This decrease has not been as low as occupants had been told by the project team it would be, which in some cases has not fulfilled their expectations. Partial correlation was found among the reported occupants' energy efficiency awareness, energy bills' change and heating systems in the rest of the cases (Figure 98).

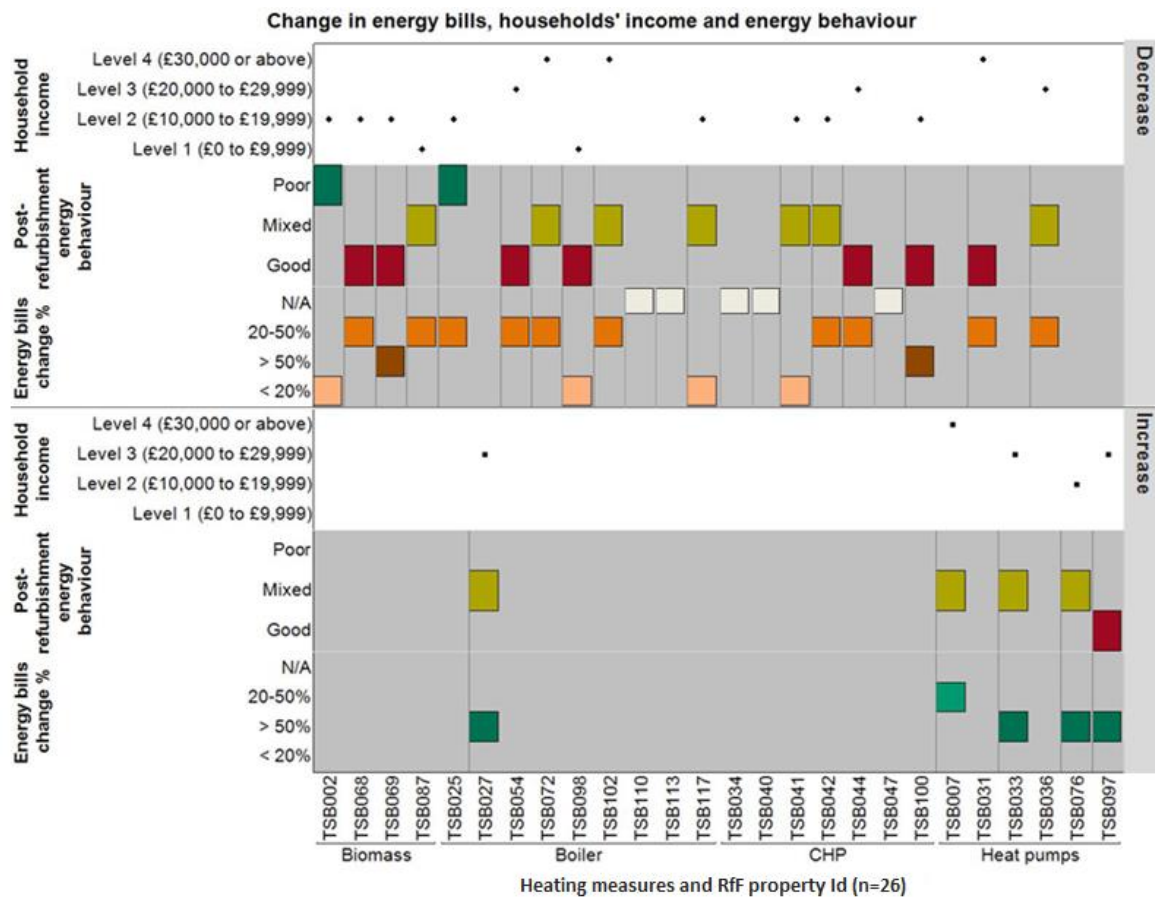


Figure 98: Households' change in energy bills, income and energy efficient awareness.

Households in the higher income bands (n=5, levels 3 and 4) with either good or mixed energy efficient awareness all had a drop in their new energy bills from 20 to 50 per cent. For the lower income households (levels 1 and 2) regardless of their mixed or poor level of energy awareness, the change in their energy bills is smaller. In the three households with mixed energy behaviour (moved into the property after works) and with heat pumps for the heating system, the change was an increase in their energy bills. However, this insight needs cautious interpretation to avoid skewing comparisons bills, as since October 2010 there was an increase to 37% of energy prices of the six biggest energy suppliers in the UK (Doward, 2013). Income levels and households' energy costs⁴⁸ will be examined in the

⁴⁸ A household's energy costs are based on the indicative electricity and gas bills provided by the occupants on the on-site visit to the author.

following sections in relation to system operation to understand whether this was due to failure of the systems or households' energy behaviour change.

8.3.1 Training provided and occupants' opinions of the systems

One of the key factors affecting occupants' opinions and their interaction with the installed low-carbon systems and measures was the level of training and demonstration provided. Except for the properties with a gas boiler as the heating system, the households had to interact without having any previous experience or tacit knowledge of the new innovative heating and ventilation technologies in the RfF properties. This section first discusses the main variables involved in occupants' introduction and overall training on the measures. This is followed by occupants' opinions, the relevant training provided and finally the specific heating and ventilation systems and controls installed in their properties.

8.3.1.1 Training provided on the systems:

The main variables in occupants' introduction to the measures are: the time that the instruction or training took place, the type and the person(s) who have provided it. In the pre-refurbishment stage only seven out of 26 households had an introduction and 'wash-up' meetings with the project team, low-carbon system agents and other RfF residents. This has involved basic information about the scale of the low-carbon and Passivhaus refurbishments and about the measures and systems whose installation was planned. The information in this introductory stage varied from vague discussion on eco-friendly houses to more specific information for the measures and technologies (e.g. insulation type, glazing and heating systems, etc.) incorporated into the RfF refurbishment. In just a couple of cases occupants were also informed about energy-saving lifestyle issues. Although this may have helped some of the occupants to understand the scale and type of intervention, in some other instances the information was found to be overwhelming and at times

confusing. For instance, in case TSB042 occupants had attended meetings with other RfF residents; although they were satisfied with the information on solar panels and the glazing systems, they also thought that:

...there was a lot more we realise; I mean, there was lot of stuff that were talking about that they didn't really apply to us but there were several people representing different companies... (Occ. TSB036).

a. *Training/instructions timing:*

Regarding the time the training occurred three main groups emerged from the sample: during works, after completion of the works, and a few months after occupants had started living in the RfF property. In the majority of the cases (n=17) the hand-out and information was generally provided on the completion of the refurbishment (Figure 99).

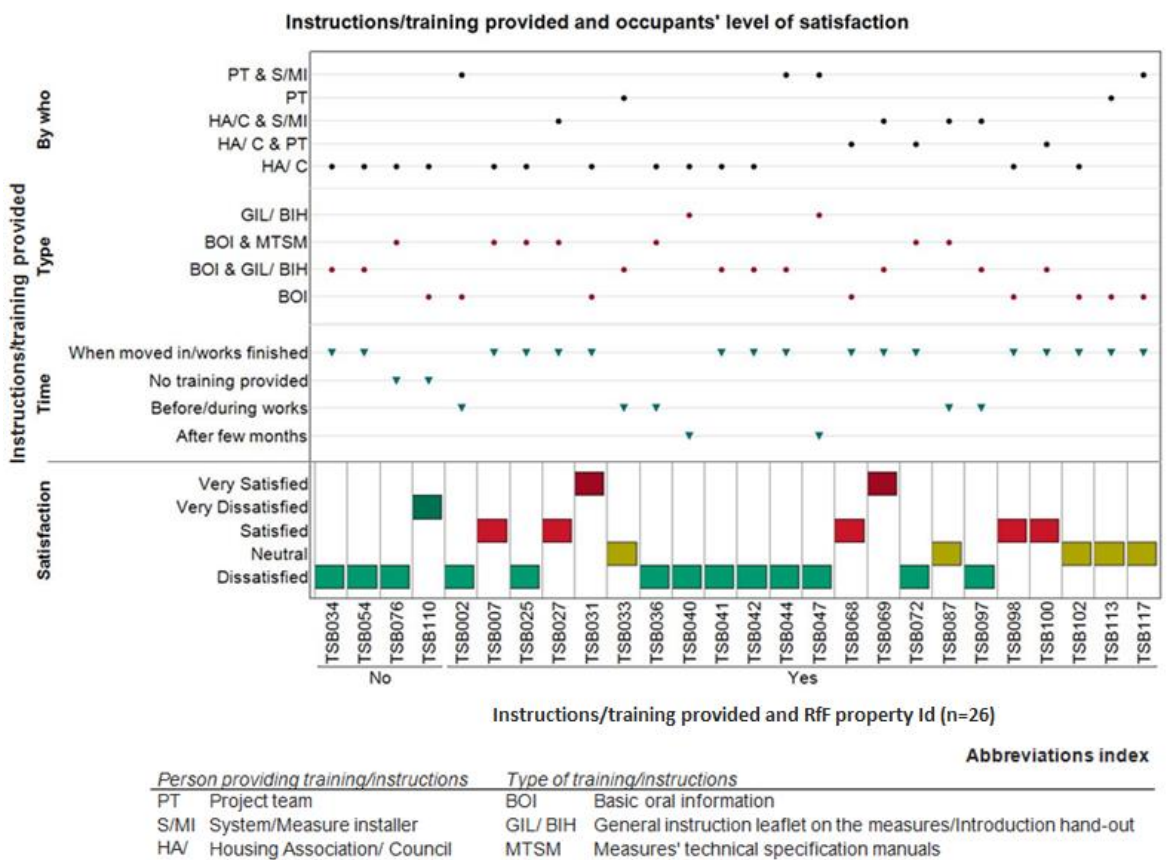


Figure 99: Instruction and training provided and occupants' level of satisfaction (n=26).

For the households that had not been relocated during works only three cases out of eight had an introduction to the measures during the works. Although it would be expected that for the households that lived in the property it would have been more straightforward to get information and a demonstration of all the measures' installed controls during the refurbishment, only one case (TSB087) had demonstration of the heating systems controls. In this case the depth of the information was clearly a consequence of occupants' personal interest and proactivity to research and ask about the installed measures. The good rapport they built with the project team and technicians allowed them to have a better level of training and demonstrations several times during works.

...only really basic stuff [instructions/training] ...I mean I was here for most of the time so I learned a lot from the guys that were putting in [systems installation] because I like to watch what they were doing and I used to ask questions so did my son and that was really helpful ...as for the end of it I've got a manual for the boiler ...the panels [solar thermal] there was no instruction for it really because it's going to do its job anyway... (Occ. TSB087)

The timing of the instructions provided to the occupants was crucial as information provided too early or too late was found to not be well received or add to occupants' understanding of the new systems and controls. Therefore, in cases like TSB072 occupants felt that the introduction process, conducted immediately after they moved in, was rather overwhelming in terms of remembering and understanding the demonstration of each measure installed. This demonstration was provided by different people in a one-off visit and the occupants had not had any previous interaction with the systems. In a few cases (n=4) occupants had been merely introduced to some but not to all measures installed whereas training was delayed up to seven months after completion of the works. In other cases like TSB042, 036 and 110 occupants were still expecting⁴⁹ measures to be explained

⁴⁹ This delay was counted until the day of the household's interview.

and someone to train or provide them with other types of information for the combined systems installed:

...we were supposed to receive a booklet manual with instructions how we needed to operate them [heating and ventilation system] but we've never received it ... (Occ. TSB036)

Although this delay may have had a significant impact on some occupants' interaction with the measures, there are also cases like TSB069 and 031 where occupants report being generally satisfied considering that:

...the systems [space heating and hot water] were all automated so we didn't really to know much ...we've been told how to use it ...about a month later...but pretty much everything was programmed on how it should be for this property and all the controls just worked themselves really... (Occ. TSB069)

Or

...I think they've told us what we've needed to know ...this particular contractor he wasn't able to show us because he didn't know himself ...but they gave some numbers [to contact technicians] (Occ. TSB031)

b. Type of information:

The type of information varied in the sample from a quick demonstration to a single-page leaflet or booklet with very broad information on energy issues, and not always on the controls of the measures installed. Three main types of instructions were found in the sample: basic oral information on the systems, general instruction leaflets on the measures (or introduction hand-out booklet) and technical specification manuals of the systems/measures installed in the RfF properties. These types were often combined or followed by a visual demonstration on system's controls (Figure 99). In a large number of cases (8 out of 26) occupants had merely oral information on the new low-carbon systems. Only two of those households also received a demonstration of some systems' controls.

An instruction leaflet with general information on the measures and an introduction booklet for the RfF low-carbon house were the only types of information provided to the occupants in two other households (Figure 99). And only in nine out of 26 properties was basic oral information combined with leaflets with general instructions for how to use some of the heating controls. The leaflet often involved simply a laminated sheet with instructions for the Wattbox intelligent control:

...one A4 for the Wattbox [instructions leaflet for heating control]... I don't know how to work it well basically on the Wattbox it says ON/OFF and that it so that's I rely on... (Occ. TSB042)

and

...the only thing we've got two three bits of paper for the Wattbox [heating control] ...it's all written down there and it's how it's working ... (Occ. TSB047)

In other cases like in TSB040 and 033 the leaflet provided information on energy efficient behaviour: how occupants could change their practices to maximise energy benefits and savings. This dealt mainly with issues like the amount of water when boiling a kettle, etc., but not on the measures installed in the RfF property.

...they did gave me like a booklet of this house and told like what they have done and a sheet of paper about the Wattbox [heating control] ...but it didn't really instruct me properly how to use and I am still not 100% on how to use them [systems/measures]... (Occ. TSB041)

Information about the refurbishment intervention of the systems/measures installed together with suggestions for energy efficient behaviour was provided in a hand-out booklet. However appears that in most of the cases occupants found the booklet information too detailed or long and so they have not read it.

...the manual [house booklet] explains how the main “ethos” and concept of the eco-house is, for example if you make hole in the walls you need to [seal] it because of the insulation... (Occ. TSB033)

Occupants’ interest in measures’ controls was constrained significantly by the type of information when they were left with technical specifications manuals for installation and maintenance of the systems, and many of those (n=7 cases) not even in English (e.g. manual written language Italian or German).

[Training/instructions provided]...no, none at all...they [builders/technicians] were coming doing a work and then leaving, whereas the housing association didn’t [know] about the measures to give the information...[male and heat pump boiler manual] he looks at it every now and again...but it’s complicated, it’s mostly wiring diagrams for the inside of it...(Occ. TSB076)

Clearly the content of the manuals was eminently too technical for people with no technical background or expertise on such combined systems.

...we’ve been left with a manual of the boiler instructions and the shower instructions...[ease to understand] not for a normal person I think if you obviously know about boilers and things you would understand it ... but for the average person no, not really...(Occ. TSB025)

c. Problems with people providing the information:

The key person(s) (‘housing officer’) providing the information have also played a significant role in occupants’ post-experience with new systems and measures’ controls. The main people involved in the instruction/training process were a person from the housing association or council, the project team (e.g. project manager, architect, etc.) or the installer of a specific system and measures’ controls. However, the constraints have not always lain with who was providing the information to the occupants, but to a great extent in the knowledge that this person had to offer on the systems and measures installed, as

well as on the rapport occupants had with this key person. The person involved in the training in 13 cases was someone from the local authority or house association who in most of the cases was not aware of the systems and did not have any technical expertise to introduce and train occupants on the specific measures.

...I said to the council man the other day that I need someone who knows what are we talking about [heating system] to come around...(Occ. TSB041)

This aspect may explain why in twelve out of thirteen cases in which the key person for training was someone from the housing association or council occupants had no demonstration of measures' controls. Occupants that received information on the measures from the project team and systems' installers also reported issues related to lack of knowledge and expertise on the specific low-carbon systems. Therefore there are cases like TSB033, where occupants who experienced a problem with ASHP boiler explain that:

...the people who came to repair [ASHP boiler] they had no idea how to switch that boiler properly....you begin to think...did they ever had a test round with the boiler...even the person who came for the boiler [ASHP boiler] he didn't know about the Wattbox [heating controls]...(Occ. TSB033)

In other cases like TSB87 occupants report having a very mixed understanding of the purpose of the biomass system and controls as different people gave them different instructions. And in case TSB100 occupants had to discover for themselves different practices to fix problems with their CHP boiler like rebooting it, as neither the engineer nor the technician knew how to fix the problem.

[occupant talking about the CHP technician]...he is self-taught because the he came and he didn't know how to do it [fix CHP boiler], he was reading the manual...I don't want to touch it because it's expensive as well ...the only thing we do is to reset it when it's not coming ON... [occupant demonstrates how to reset the boiler] (Occ. TSB100)

Another issue that came up in the majority of the cases in the interviews was that people on the project team, site management, contractors or installers of the measures were often changing due to redundancy or companies' liquidation issues. This had a significant impact on the level of introduction to the measures as the key person(s) conducting occupants' training was often unaware of the measures and systems installed in the RfF property.

To a large extent (14 out of 26) occupants were overall dissatisfied with the insufficient level of training they received on the new systems (Figure 99). In five cases occupants were neutral about the training process, feeling that they had not received enough instructions and they would prefer a measure by measure visual demonstration of each system and measure installed. This has been a serious limitation of the training process as only in ten cases out of 26 did occupants have a demonstration of some (not always all) of the systems installed in the property. In this context occupants' main requirement in all cases was a measure by measure visual demonstration from an expert on all the measures/systems installed in their property in the first weeks after they moved in. Although the measure by measure visual demonstration was a prerequisite for the RfF competition process, this appears not to have been employed in the sample sufficiently.

8.3.1.2 Occupants' opinion on the systems and controls

In this section occupants' opinion on the low-carbon systems and controls installed for heating and ventilation in the sample is discussed.

a. Gas boiler heating system and conventional controls

Occupants' opinions on the new gas boiler system are generally neutral as they had similar past-experiences to the previous heating systems. In the majority of cases the training provided seemed to assume that occupants were rather familiar with such system controls

and therefore was limited either to a basic demonstration of the programmer settings or to technical manuals of the boiler and controls. Even in such conventional heating systems, occupants' training was generally lacking an overall demonstration that included all controls related to the heating system as a whole. Thus, in a couple of cases like TSB072 and 117, occupants had no clear understanding from the training provided and therefore they tended to rely on the programmer's technical manual to set up the boiler based on their preferences; in other cases like TSB113 default settings were retained as no other information/instructions were given. In this respect training could also involve a demonstration of the direct controls on the boiler, programmer settings that diverge from defaults, and thermostat and thermostatic radiators' valve controls, followed by the ways all these controls can be combined and best used according to occupants' needs and comfort preferences.

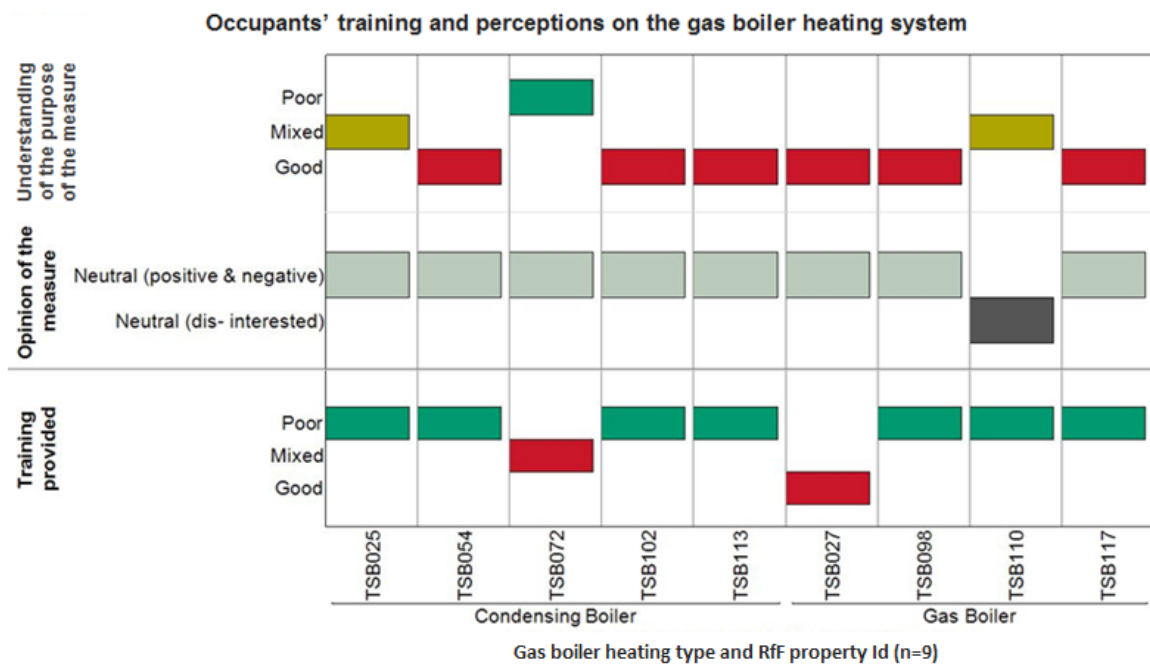


Figure 100: Occupants' opinions of the boiler system and level of training provided (n=9 properties).

As regards occupants' opinions of the measure, although initially they were feeling generally positive about having a more efficient boiler, this was partly affected by the

operation problems they have experienced (Figure 100). Therefore in cases like TSB025 and 117, the system could not perform as expected due to installation faults like the size of the radiators' pipes interfering with radiators' temperature. In a couple of cases (TSB027, 072) occupants' opinions were affected by the lack of control due to malfunctioning of the boiler system to back up the solar thermal panels installed for hot water. This in the case of TSB072 may explain occupants' poor understanding of the purpose of the combined heating system installed. Most of the occupants have generally a good understanding of the purpose of the gas boiler as a heating system as a result of their previous interaction with similar systems.

In 4 out of 9 properties an intelligent system like Green Energy Options' Trio⁵⁰ monitor display was also installed to add to occupants' heating understanding and usage by monitoring for instance space heating and hot water operation, heating settings, preferences, etc. However, in none of the properties was the system functioning or had the occupants been trained to operate it, thus in all four properties it was found out of use.

b. Micro-CHP heating system

Domestic-scale combined heat and power (micro-CHP) heating systems controlled by Wattbox intelligent controls have been a new interaction experience for all households (n=7) in the sample. In all cases of occupants with either a positive (n=2) or neutral opinion (n=3, both positive and negative views) about the micro-CHP system, they highlight that they are generally positive once the combined system (CHP boiler and Wattbox control) is working properly. Therefore, in some cases like TSB040, although the occupant particularly likes that the system generates energy, at the same time the occupant finds it very complicated especially due to the lack of control over it. And in case TSB100

⁵⁰ The Green Energy Options Trio is an energy use display and monitoring device of over 30 appliances providing an in-depth view of where the energy is use in the household.

both occupants believe that the whole system is a good concept only if the boiler communicates properly with the Wattbox and temperature sensors.

Two main factors were found to affect occupants’ opinions of micro-CHP:

- the level of training they received on the measure; and
- the problems or malfunctions occupants have experienced due to the system’s installation faults.

Occupants’ opinions of the training and instructions they had from the project team on the specific measure were generally negative. Except in one case (TSB100) were occupants had mixed views, the majority of households considered the information as being at poor or very poor levels (very poor: occupants did not know how to work the measures at all) (Figure 101).

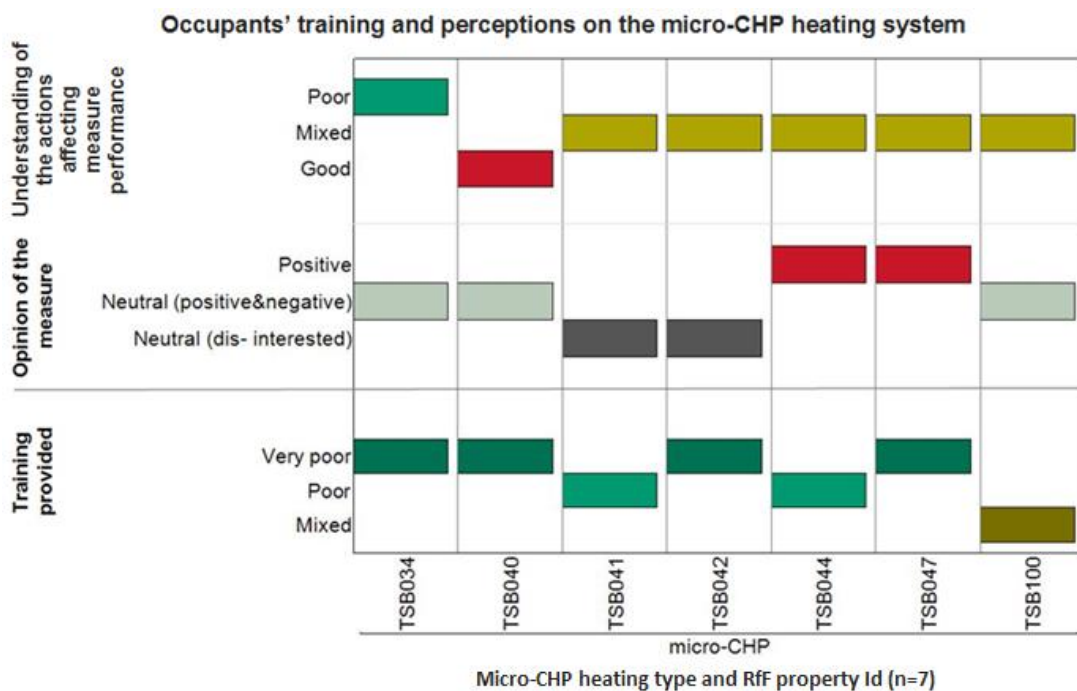


Figure 101: Level of training provided and occupants’ opinions of the micro-CHP measure (n=7).

The main reasons for being dissatisfied with the training were that occupants had been told by the project team ‘not to touch’ the micro-CHP boiler (cases TSB044, 047, 034 and 100)

or they had been left with technical specification manuals that have not aided their understanding of the purpose of the measure or actions that may affect its operation.

The limited information they received for the micro-CHP boiler in some cases may be generally justified by the fact that it was designed to be indirectly controlled by the Wattbox, since the direct controls on the boiler are ‘scripted’ designed for passive users and are generally a complex matter that requires technical knowledge. Nonetheless, as occupants report in cases TSB041, 040 and 042, another factor that contributed to the limited information provided was the lack of technical skills and specialised knowledge of the specific measure of the persons who were assigned to train them. In order to understand occupants’ overall opinions of the micro-CHP heating system, the level of information needs to be seen together with the information received for the Wattbox heating control discussed in the following section. Other negative aspects reported that affected occupants’ opinions were the malfunction of the whole heating system due to installation problems and a lack of communication between the intelligent controller and boiler.

c. Heat pump (HP) heating system

Two types of heat pump heating systems were installed in the sample: ground source (n=2 GSHP) and air source (n=4 ASHP), combined with different types of conventional and intelligent controls. In cases of GSHP like TSB076, occupants’ opinions were generally negative as the system never worked properly and thus could not perform to its standards⁵¹. In this respect the problems in the installation of the GSHP system have highly affected occupants’ opinions as they did not have the opportunity to interact with either the system or the Wattbox controls ‘as designed’. In the case of TSB036, occupants’ mixed

⁵¹ Due to installation faults the GSHP system was not able to provide the required heating and hot water to the property and for this reason after a couple of months the system was temporarily out of operation, replaced by the previous old gas boiler.

positive and negative views of the system were mainly due to the lack of control they had over Wattbox to set up the heating system according to their preferences. Although occupants in both cases had a good understanding of the purpose of the combined heating system, this was a result of their own proactivity and not of the training provided (Figure 102). Similarly, occupants' opinions of ASHP vary in the sample in relation to the training provided and the system's controls performance. In three out of four cases poor and mixed training was correlated with negative or neutral opinions (both positive and neutral views) of the ASHP system and controls. Therefore, in case TSB033, for instance, the occupants' poor and confused understanding of the purpose of the measure was mainly the result of their poor training; they reported that no one had explained them what the ASHP system is, what it does and how it works. The only information given was to press for more or less heat in the Wattbox. Also, they had negative views of the noise due to the malfunction of the system. In the case of TSB007 occupants were negative due to the malfunction and lack of control they had over controls (Optima Design Controller).

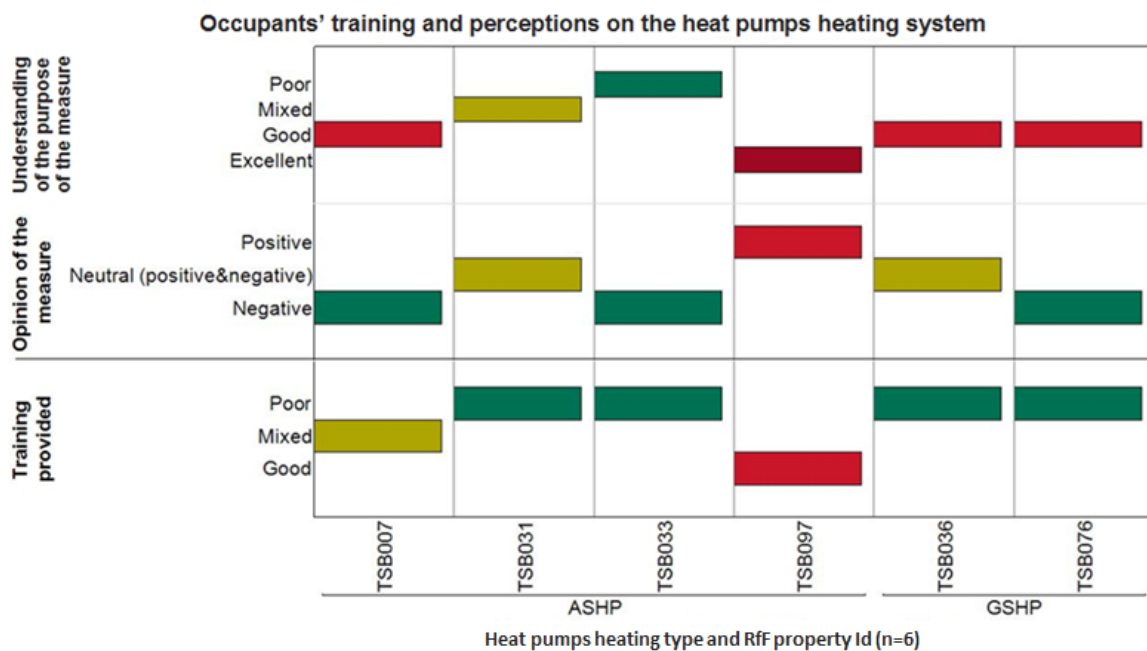


Figure 102: Level of training provided and occupants' opinions of the heat pump heating system (n=6).

There is only one case (TSB097) where the good level of training provided on the ASHP systems and controls has significantly contributed to occupants' positive opinion and excellent understanding of the measure's purpose. The factors related to malfunction or installation faults of the heat pump systems and measure controls are discussed in the following sections.

d. Domestic biomass heating system

Occupants' perceptions of the domestic biomass systems controlled by conventional or intelligent controls were found in the sample to be divided into either negative or positive (Figure 103). Although in the majority of biomass cases (3 out of 4) occupants received a satisfactory level of training as well as their level of understanding of the measure's purpose was good, factors like the system itself and the type of the controls have affected their opinions negatively (2 out of 4).

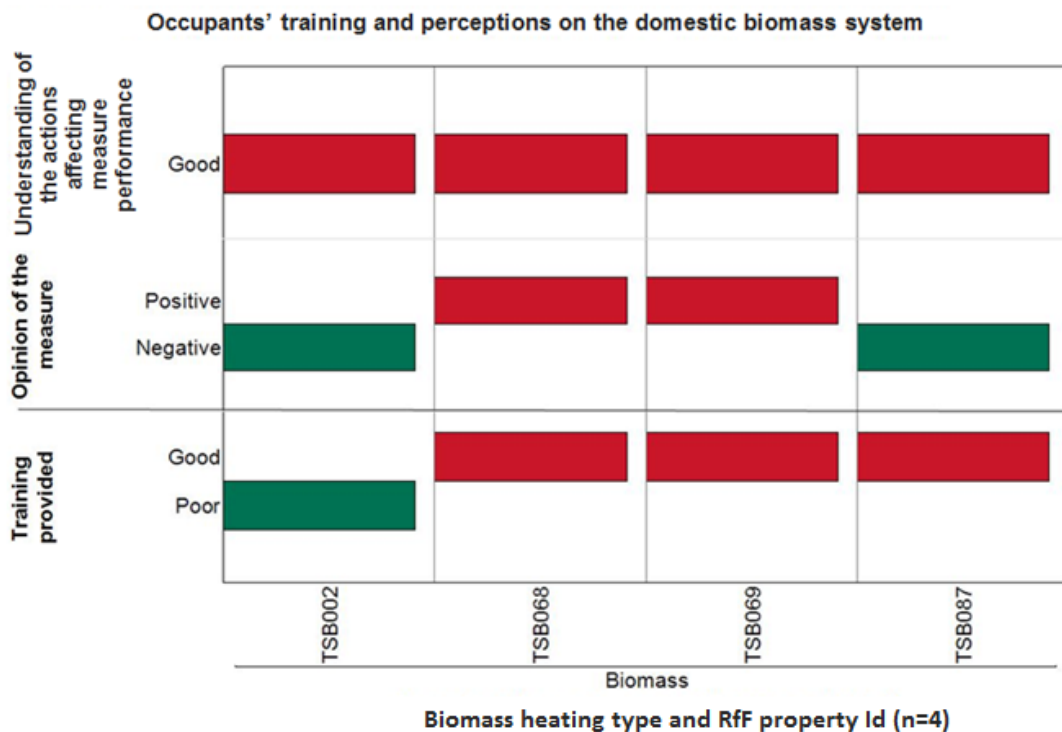


Figure 103: Level of training provided and occupants' opinions of the domestic biomass heating system (n=4).

Therefore in cases like TSB002 and 087 the issues that emerged were related to the Wattbox operation and lack of control and particularly to the feeding process of the biomass boiler. On the contrary, with the other two cases in the sample (TSB068, and 069) which had a pellet store/hopper and auto feed system, the feeding process was conducted manually. As occupants report, this aspect has negatively affected their everyday routine and lifestyle; the fact that the biomass boilers were located inside the house (living room and utility room) has been another negative aspect of their opinions of the measure.

e. Intelligent controls in heating systems

As discussed in the sections above most of the heating systems in the sample (n=13) are operated by intelligent controls like Wattbox⁵² (n=12) and Optima Design Controller (TSB007). To a large extent (n=9) occupants received mixed information on the controls and this was highly dependent on the person and level of expertise they had on the specific measure. The information for the Wattbox was provided either by someone from the project team at the time of the property's handover or by a technician after a problem with the measure or a malfunction of the combined system occurred. The instructions provided for the Wattbox in most of the cases were very basic, like instantaneous settings to press a button for more/less heating or hot water, but none on personal settings or on the information regarding the electricity generation and consumption. As regards the training the main issue highlighted by all occupants was the lack of a practical demonstration on Wattbox advanced settings that allow users to set up their occupancy and heating preference controls. In this respect the majority of the occupants found both positives and negatives in the intelligent controls, which for some occupants (n=7) also resulted in a mixed understanding of the measure (Figure 104 below).

⁵² The Wattbox is an intelligent heating device (space heating and hot water) to control the heating system. The device is a "smart" home heating controller that automates time and temperature settings by learning from householders' energy habits.

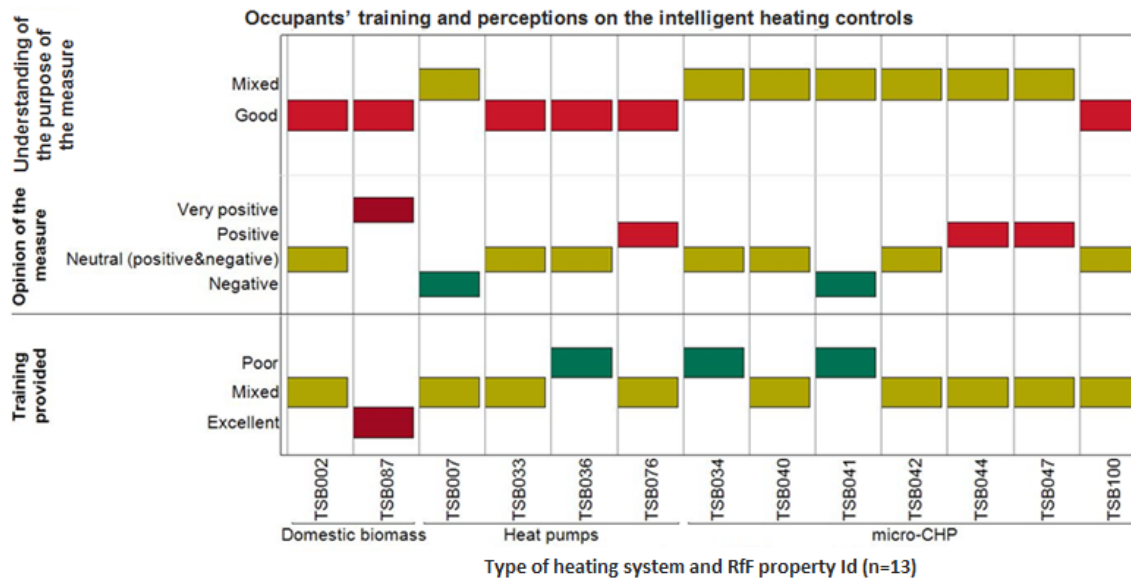


Figure 104: Level of training provided and occupants' opinions of the Wattbox intelligent control (n=13).

Thus, although some occupants may have considered the Wattbox controller a nice concept that is easy to use or a clever system that 'learns' from their routine when it is working properly, others feel like the controller 'as designed' allows very limited control over the heating system, deterring them from setting up their instantaneous comfort preferences. As occupant TSB041 reports,

...I don't particularly like the Wattbox; I don't find it complicated, I just find it irritating...and I know I shouldn't really be having to touch it; [it] is supposed to doing it all for me ...in a weird way I cannot like that ...I don't like not being in control if that makes sense...(Occ. TSB041)

Hence in the case of the intelligent controls three main factors have affected occupants' perceptions: the lack of demonstration of advanced settings and insufficient instructions to operate the combined heating system as a whole; issues related to operation failures (like for instance the controller not communicating with the heating system – HP boiler, heat pumps, biomass- or often displaying the wrong indoor temperature, etc.); and finally the scripted design of the controller that constraints occupants' full control.

f. Solar thermal water heating system

In fifteen cases the heating systems discussed above were combined with solar thermal panels, as a backup system, controlled again by the heating system’s intelligent or conventional controls. No significant correlation was found among their information/training, occupants’ opinion and understanding of the measure. Thus, despite the insufficient training in most of the households (n=11), occupants’ opinions appear either neutral or positive. Some of the occupants (n=3) who report a lack of interest in the measure also have a poor understanding of its purpose and are confused about whether it generates electricity or provides hot water (Figure 105). The negative issues again are mainly related to the system’s malfunction and problems with the hot water supply like the water’s temperature, especially in warm months, when the heating system is turned OFF (n=3 properties).

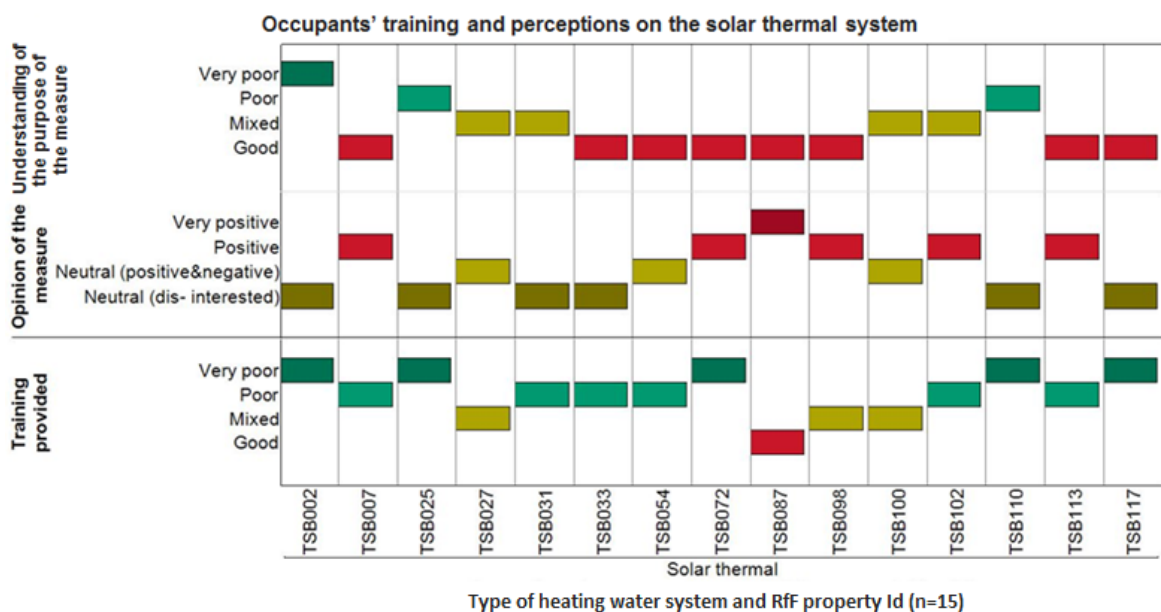


Figure 105: Level of training provided and occupants’ opinion of the solar thermal system (n=15).

However, there are also cases (n=6) where occupants’ experience with the solar panels has positively affected their opinion, like in case TSB072, in which the occupants have not turned the boiler for hot water ON for 5 months as the solar panel system was providing

sufficient hot water for their needs. In other cases like TSB098 personal interest trump technical failure, as occupants feel positive about the measure not because of bills' reduction or adequacy of the hot water supply, but from their personal interest in low-carbon technologies. In a few other cases (TSB117, 054 and 033), either occupants' good understanding of the measure's purpose or training are related to occupants' neutral opinions of the measure.

g. Photovoltaic systems and controls

Occupants' perceptions of the photovoltaic system are similar to those of solar thermal systems. In the majority of the cases (n=20) occupants' opinions of the measure are neutral. In three of these cases they feel uninterested and again confused about the purpose of the photovoltaic system installed. As for the rest of the cases (n=17), although occupants are aware of and positive about the benefits from the measure, they consider rather negative the fact that they are not aware of the electricity the system generates and how much they benefit from it (Figure 106). To a large extent (n=21) this is due to generally poor training and information provided on the measure. In 8 out 11 cases with Wattbox controls occupants have not received an explanation of either how to read the information on the intelligent controller of their electricity generation or how to use their electric appliances efficiently. In the rest of the cases occupants had no information or feedback on the amount of electricity they generate (Figure 106).

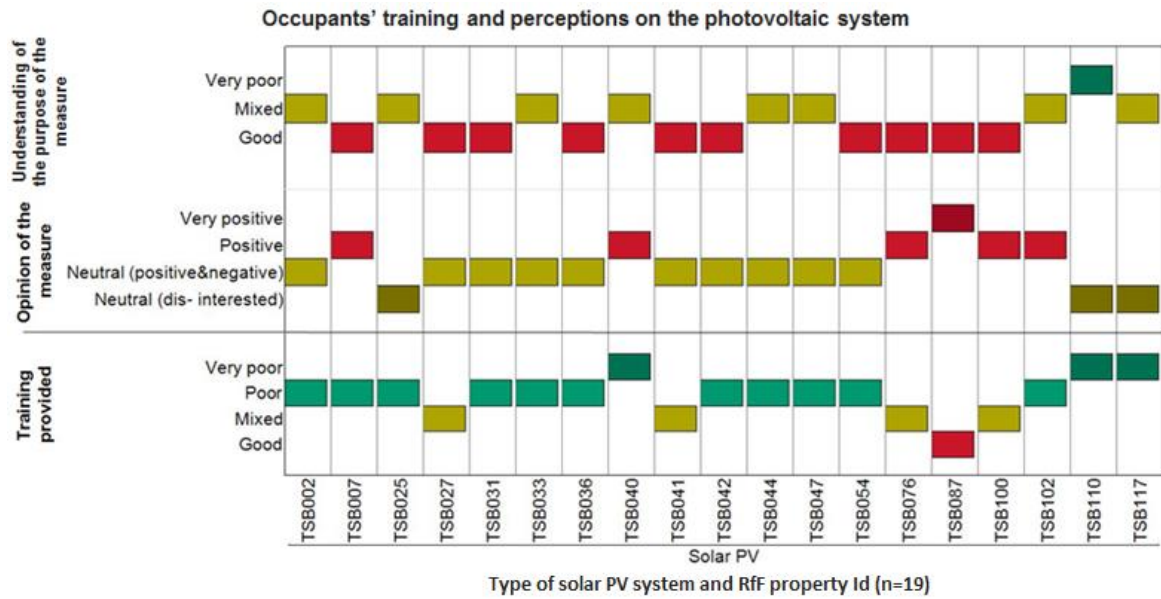


Figure 106: Level of training provided and occupants' opinions of the photovoltaic system (n=19).

In some cases like TSB031 and 087 occupants take their electricity bills into account as feedback to understand the slight reduction they had in their bills as they were not been informed that bills do not include PVs generation and only their net electricity consumption. However, this occupant TSB 117 correctly highlights a lack of awareness of the benefits of the measures since no one has explained whether this change in their bills is due to the consumption and behaviour change or to the electricity offset from the solar panels. Only in case TSB033 did an occupant have the information to monitor their electricity generation through a website; however, even in this case the occupant notes:

...the main 'selling point' [for getting involved in the RfF refurbishment project] when they came to me was that in the property you are going to gain back more than 2% on your bills [from PVs] ...and that hasn't happened at all; in fact [it] has increased ... (Occ. TSB033)

In cases TSB025 and 027 with the Green Energy Options Trio display installed, the monitoring system never worked to provide them feedback on electricity generation and their energy use. In this respect despite the positives that generally all occupants find in the concept of the photovoltaic system their main concern lies in the fact that:

.... I am still paying the same amount in my electricity bills, so it is not benefiting me at all ... (Occ. TSB002)

This aspect also affects their understanding of the purpose of the measure as in many cases (mixed, n=8) they have not had any practical experience of how the system works and how they can change their routinised practices to benefit from it. In none of these cases occupants were aware of neither being part of the Feed-In Tariffs scheme nor of the tariff rate they were using and more importantly who was receiving the payment from their electricity generation or export.

h. Mechanical ventilation systems

For both types of mechanical ventilation occupants' opinions were neutral, with most occupants (n=12) being uninterested in the system; in 6 cases their opinions were affected by both negative and positive aspects (Figure 107).

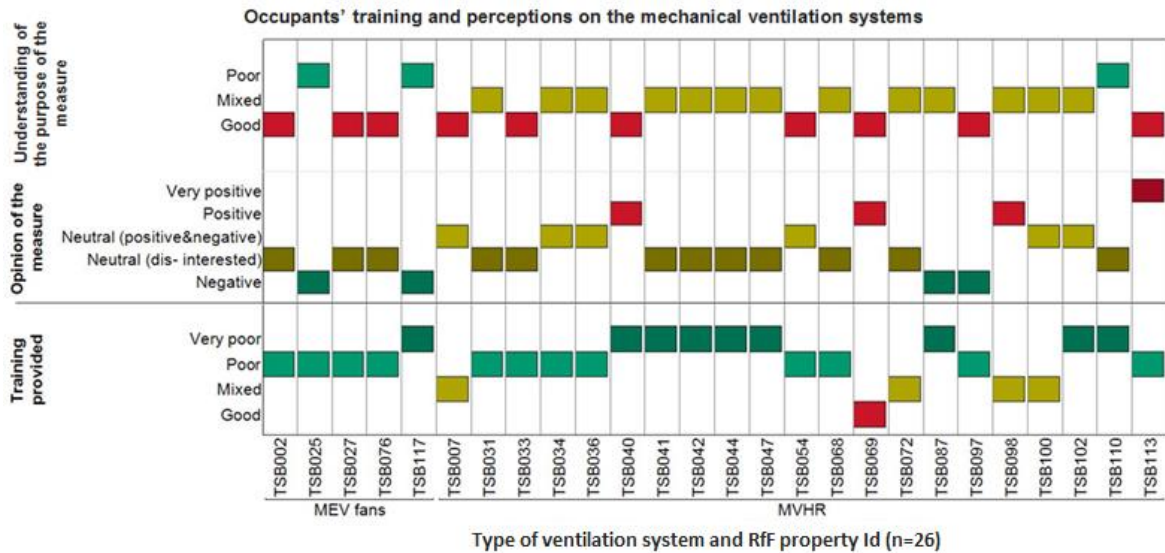


Figure 107: Level of training provided and occupants' opinions of the ventilation systems (n=26).

In properties with MVHR systems occupants' opinions were highly affected by the poor training and information provided, resulting also in a mixed understanding of the measure's purpose (13 out of 21). Along with the poor training other negative factors

reported were: occupants being sceptical about whether the measure was working properly or not as they have not found any change in the indoor air quality; noise issues, particularly when it was windy outside; issues due to installation problems of the system blowing cold air; insufficiency to take all the steam out from the wet rooms therefore occupants still open the windows; with all these occupants' feeling that they have no control over the system. Occupants' negative opinions of the MEVs installed were mainly due to installation issues that constrain occupants from having full control over the measure. Installation issues and measure controls affecting occupants' perception and interaction are discussed in the following sections.

8.4 Problems with controls of systems and measures installed

Occupants' heating post-experience was found to be related to the level of training and control they had over the system, which was also found to be largely constrained by the malfunctioning of the low-carbon systems and their controls. In this respect this section explores the causes that may affect occupants' interaction and highlights the key issues that occupants reported or were captured by the post-occupancy evaluation survey.

a. Technical problems and installation faults

A common technical problem that emerged in the sample was the lack of communication between the low-carbon heating systems and Wattbox heating control, which resulted in problems in both space heating and hot water. Therefore, in 4 out of 7 cases (TSB042, 040, 047, 100) with micro-CHP boiler this issue has reported as a problem of the sensors sending wrong signal to the Wattbox and consequently the latter to the micro-CHP boiler. Therefore in case like TSB042 the mean indoor temperature was captured the day of the interview at 19.4 °C when the Wattbox was showing room temperature at 40 °C (Appendix

20, Figure 165) not allowing the proper function of the boiler to occupants comfort preferences. As the occupants explain,

...[Wattbox] it worked for a couple of weeks and then I have to have the Wattbox people back again...and is still not working now ...I don't know if that is due to the sensors ...it doesn't read properly at the moment it says [it] is 40°C in here...the heating is doesn't come ON it supposed to know when I am in when I am out ...it doesn't do anything of that, no it doesn't work... (Occup. TSB042)

Similarly in most of these cases (n=5, TSB044, 034, 047, 040 and 042) the lack of communication between the CHP boiler and the Wattbox has also been a problem in hot water heating, several times leaving occupants without hot water, which in some cases was for several days (e.g. TSB042, 034, Appendix 20, Figure 165). Similar problems of systems' communication were found among GSHP, ASHP and the Wattbox controller. However, in the case of TSB076 the GSHP system has not worked properly not only because of the lack of communication between the heat pump boiler and intelligent control but mainly due to serious installation faults of the heat pump (insufficient depth of the horizontal loop system to reach ground temperatures and provide high collection efficiency).

Extreme temperatures in the water tank followed by high levels of noise in the CHP boiler unit or installation leakages were some other problems reported (e.g. cases TSB047, 040 and 042),

...[micro-CHP boiler] it was a hell of a noise and it's been going up and up and up [temperature] and we couldn't turn it OFFit was awful... (Occup. TSB047)

And in the properties with a shared biomass boiler (TSB068 and 069) occupants reported problems with the system when their demands for space heating and hot water ran concurrently in the two houses:

...I think because it's controlled [biomass boiler] by both the houses, I think that if we put the heating ON at the same time or they have a bath at the same time ...cause that's the only time we've had a problem with it ... (Occup. TSB068)

In the case of TSB102, with communal gas boiler and solar thermal panels for hot water, although the shower tap was replaced with a new mix tap in the basin, the previous basin taps were kept. Occupants complained about 'steaming hot water' when the heating was off that they were unable to regulate and this affected their routinised washing practices. Problems were also reported in the more conventional heating systems. That is, in cases like TSB025, 027, 054, 072 and 098, occupants have run out of hot water due to installation issues of the combined solar thermal system and the gas boiler back up. These problems were mainly due to insufficiency of water pressure and temperature. Therefore, in the case of TSB027, although the boiler fired up it was unable to provide enough hot water to back up the solar thermal. Occupants in this case have indicated a lack of a control panel that could show them the level of hot water from both the solar thermal and boiler (the only control left to them was the water temperature adjustments).

An issue reported as a malfunction of the Wattbox controller that has been a major problem for occupants in setting up their comfort preferences was the incapability of the system to respond to their instantaneous settings. However, this issue has more to do with the scripted specifications of the measure itself and the lack of information/training provided rather than to a heating controls faults:

...we need to know how to have the heat constant without needing each time to press for more heat because it gets OFF ... (Occup. TSB041)

In the case of TSB040 the occupant believes that if someone had given more information on the measure and demonstrated how to set up their preferences in Wattbox they could

have saved money, as when the system is not working properly the house is overheated with temperatures up to 35°C degrees and no hot water supply.

The innovative concept of the Wattbox controller is its design to switch heating on and off, learning from a household's occupancy and occupants' behaviour relating to electricity and hot water usage. Its scripted ability also does not require time clock settings by the occupants. These are the issues that for some occupants entailed lack of control over the measure. The fact that the measure requires a certain time (days) in this process of 'learning' occupants' preferences was the issue reported as a measure fault as it did not allow their instantaneous preferences. Occupant TSB041 explains that the problem with the Wattbox controller compared to the standard programmer she used to have is:

... with this if you want the heating ON you press more heat it heats up but then it gets to certain temperature and clicks OFF but then it won't click back ON again ...you have to keep pressing every time ... (Occup. TSB041)

The problem in other cases like TSB100 is that when occupancy varies made difficult for the intelligent control to understand occupants' preferences and occupancy slots to be adjusted as they had no access to Wattbox advanced control settings to set up their occupancy schedules was unlocked for the users.

In the case of the micro-CHP system the controls were very limited, applying only to setting changes, with occupants having no indication whether the problem was due to malfunction of the Wattbox or the boiler. In a POE demonstration of the Wattbox occupant TSB100 explains the level of controls left and systems faults:

...if you want more hot water you press that ...if I want heating I go to that one ...if I go to the advanced controls it [is] supposed to tell you how warm [it] is outside when the heating should come ON and OFF but that doesn't work... and this is the technical data and this is all the sensors that [are] not working so...that's how we

turn our heating ON...but this is all password encrypted so you can't really do anything, you know change times ... (Occup. TSB100)

A difference of temperature of more than ± 1 degree Celsius among the Wattbox display, the physical monitoring and on-site measurements was found in six out of 12 cases on the day of the interview. This inconsistency may explain the problems reported with the temperature sensors, with the intelligent controller in most of these cases displaying higher temperatures than the ones measured on-site (Appendix 26). This aspect has a significant effect not only on occupants' control but also on understanding and reporting of their comfort preferences.

Other installation faults in heating measures were found in the thermal blinds (TSB044) that resulted in the measure not being operated completely, as in all windows the blinds were glued into the mounted top and fell every time occupants tried to use them.

Monitoring systems like the Green Energy Options Trio display had different operational problems in all four properties installed. Occupant TSB027 explains that the monitoring system was initially working, showing the electricity usage of all items in the house:

...but after about six months of using it [monitoring display] they [the monitoring company] found that it wasn't properly connected to the internet so it wasn't really reading the appliances ... (Occup. TSB027)

In the case of TSB098 the occupant explains that the system never worked as she was told that it was still being updated and although she was told that someone would come back to explain the system and put it in operation this never happened. In comparison, in case TSB054 the issue was not only that the monitoring display never worked but also that it was installed at a height that constrained any interaction with the user.

Problems were also reported in the cases of properties with mechanical ventilation systems and controls. A common problem in some of the properties (TSB100, 087, 007 and 102) with the MVHR is that the system was blowing cold air during the cold months and freezing cold in warm months:

...where all is ever done was to blow cold air ...so in the winter I closed them I leave open just a little bit to avoid condensation coming back... but they don't work in the winter they blow cold in ...which is lovely in the summer you get the breeze...[when she asked] ...they [installer and technicians] all tell different stories ...I complained because it was cold in the bedrooms and the guy which the company was [MHVR installer] said that it was never intended to blow warm air; it was only intended to bring fresh air in, not to circulate hot air anyway, where the these heating people told me that what it was... I never actually got the right answer... (Occup. 087)

In most of these cases occupants prevent the circulation of cold air by closing the air valve when permitted by its design (Appendix 21). In the case of TSB102, where the MVHR system is used as a heating source, occupants reported the same problem with the blowing cold air and not being able to have control over it either from the source due to the design or from the controller due to the lack of training. Noise issues from the MVHR in some cases were either solved by the technicians or weakened due to occupants' adaptive behaviour. But this did not occur in all cases (TSB041, 007, 036 and 068), with occupants still reporting:

... [MVHR system] it makes a horrendous noise when there is wind ... (Occup. TSB036)

Design issues relating to the measures installed were found in both mechanical ventilation systems and natural ventilation. One of the problems captured very often was that the MEV extractors in the wet rooms (kitchen and bathroom) had one joined switcher with the light; in other cases although it was in a separate switcher it was placed at the top edge of

the wall or ceiling, causing a constraint due to the height of users' controls (Appendix 21, Figure 240 to Figure 244). In natural ventilation the most common design issue that emerged from the sample related to the operational problems due to the location of the kitchen window and the increased width of the wall to achieve insulation standards (Appendix 27, Figure 217 to Figure 229). Thus, in fifteen cases out of 26, occupants could not open the window above the sink because they could not reach it. As occupant TSB047 explains:

...I can't reach it unless I step on a stool step ...[before refurbishment] it was nearer – this is wider, see...I have little stool but I open the door [to move the steam out]... (Occup. TSB047)

Or

[occupant explains how reaches the window above the kitchen sink] ...I have to climb up to open it ... (Occup. TSB098)

The size of the windows and doors installed has also been a design choice that in cases like TSB036 and 054 affected occupants' interaction with the measure and consequently ventilation practices. Therefore, in the case of TSB036 the big sizes of the bedroom window and window door cause them to occupy a great space in the room, leaving very limited space for occupants' activities. In TSB054 the change of the window type from a small tilt pane to a pivot/tilt one has increased difficulty in operation. Occupants in this case cannot have full operation of the window due to its increased weight (one pane is triple glazed) and also because of the low sill plate, which creates safety issues around falling out when occupants try to fully pivot the pane. Installation and design faults also prevent occupants from fully opening the kitchen and hallway windows in the cases TSB047 and 110 (Appendix 27, Figure 218 to Figure 221).

Other measures installed for natural ventilation have not always allowed users' interaction. Therefore, the skylight roof windows installed for manual operation by using a telescopic pole has also been problematic in the cases TSB098 and 110 due to the height and weight of the triple glazed window. Moreover, in case TSB087 occupants cannot interact with the windows' trickle vents installed because they were all sealed, as the occupant explains:

...[windows trickle vents] are all sealed, [the project team] have all sealed them up cause he failed his first [airtight test] ... after the works they [did] a test and it failed, they didn't [have] the rating they wanted so ...he went around mastic all vents ...so in all windows all the vents are sealed ... (Occup. TSB087)

Other installation issues and measure defects were found in the case of TSB034, in which occupants reported condensation between all window panes when the external temperature drops. This may indicate faults in the sealing process of the windows and poor quality of double glazed windows installed. As well as installation faults of the external doors in some of the refurbished properties like TSB031, 102 and 027, as a result projects failed airtightness tests (Chapter 7, Figure 56, p. 240) due to significant draughts:

...in our front door there was a gap that I could fit my hand literally ... (Occup. TSB031)

Passive measures in natural ventilation like doors' lower edge gap in the case of TSB042 was built up bigger than designed, resulting, as the occupant explained, in significant heat losses in the living room from the unheated entrance hall and stair space.

As for design choices with an impact on users' practices, in many cases the cooking extractor fan was installed to recirculate air inside instead of releasing it through an outside vent to extract moisture and odours outside; or in other cases it was not installed at all, relying only on the operation of the MVHR (Appendix 27, Figure 245).

b. Lack of technical expertise in low-carbon combined systems

In the majority of cases with combined CHP and Wattbox systems the lack of technical expertise has also been an important constraint for occupants. In this respect occupant TSB047 explains that although different technicians -even from the Wattbox Ltd company- had tried to fix the problem of communication between Wattbox and the heating system, they could not. After some time they finally found that this was a problem of the transmitter's batteries going flat; however, nobody knew about it:

[talking about the Wattbox and the micro-CHP boiler] ...nobody knows at this end what to do, nobody knows how to service that ... (Occup. TSB047)

The lack of information on how to override the micro-CHP heating system was another issue raised by the occupants which was related to the level of control they had over the system and negatively affected their opinion and overall satisfaction with the heating system. Therefore occupants explain that:

...when the heating and everything is working fine is nice, it comes ON and it works ...what I don't like about it is that there is an immersion heater in there but doesn't work... it doesn't override the heating system ...so for example when we first moved in here we had no heating, no hot water ... we could put the immersion ... to heat ... that was a very difficult time for us so that's one of my major dislikes ... (Occup. TSB044)

Or similarly other occupants feel that:

...it couldn't be great if you could override things like these [boiler] ...I think one of the shortcomings of this is that you can't override anything ... [so do you feel that you don't have control?] ...you have no control if something goes wrong you can't say OK I've got the old system ... I'll press this button and that ...but to have to rely on someone that has to tell you what to do with the computer is not really that good...you're stacked and you can't do anything about it (Occup. TSB040)

Occupants in the case of TSB033 explained that the problems of the system's communication between the ASHP and Wattbox controller were mainly due to the lack of coordination between the different installers of the heat pump and intelligent controls. However, even in conventional heating systems the insufficient technical support that occupants had in order to solve heating systems' problems often resulted in other adverse effects. For example, in the case of TSB025, when the project manager tried to solve temporarily the system's problem by setting:

...the immersion ON and [the project manager] said that will sorted out in a couple of days...and it wasn't back then that we forgot about it ...it wasn't about last Christmas time that we've got a letter of an electric bill for £700 ...and I said hang on this can't be rightand [monitoring company] realised that the immersion has been ON for 24/7 since July... and that took a while to get that sorted ... (Occup. TSB025)

A similar issue was also found in case TSB097 with the ASHP system, in which the immersion heating was coming up every time there was heating demand, which also resulted in exceedingly high energy bills. The occupants have also reported a lack of lasting hot water. Thus they had to find different patterns in the daytime for all of the family (two babies and two adults) to shower. Another issue that the occupants had highlighted in this case was the difficulty for the project team and technical support to understand what the problem was in the heating system given that half of the people who were responsible for the project had been made redundant:

...so there was nobody really taking control of the house... (Occup. TSB097)

The information provided to the occupants for the MVHR system maintenance, like in the case of TSB047, also had a negative result on the system's performance. Occupants in this case were told by the MVHR technician to Hoover the air valves to clean them; however, this resulted in all valves becoming frail and needing technical support to fix the problem.

This lack of knowledge had a direct impact on occupants' understanding affecting interaction with the measure.

Overall these aspects clearly show that there is a lack of skills in the supply chain (building designers, builders and contractors) and this not only in the installation/design of combined low-carbon systems (e.g. CHP and solar thermal) but also in individual measures like MVHR and thermal bridging. Not only improve the level of knowledge in the building sector in high priority but also develop multi-skill professions that can ensure installation and best practice performance of the low-carbon measures.

8.4.1 Occupants' other actions affecting measures' performance

Occupants to a large extent are aware that systems' and measures' performance is affected not only by installation faults and the lack of information provided, but also by their own actions and routinised practices. In the majority of the cases occupants' understanding of their practices is related to the opening of the windows affecting heating and mechanical ventilation performance. Despite the type of ventilation system most occupants are aware that routinised practices to air the house or cultural habits of opening windows and doors affect heating performance of the house. However, when it comes to ventilation, in ten out of 21 cases with MVHR systems occupants tend to open the windows and be unaware that such actions may affect the mechanical ventilation system. In two of these cases occupants open the windows when smoking indoors when the mechanical ventilation is constantly on 24/7. In the rest of the cases (n=11), even though occupants explain that they are aware and understand that window opening affects the MVHR system performance, in 8 cases they do open windows. As they explain, this is because they feel that the system's supply is not enough and they need to bring more fresh air in the house by opening the windows. As regards the other low-carbon systems installed in the RfF sample, occupants generally report that none of their actions affects systems' performance.

8.5 Occupants' interactive adaptivity

Interactive adaptivity approaches examined occupants' physiological and behavioural adaptations, related to their heating and ventilation actions in order to restore their conditions of comfort. As mentioned in the literature review (Chapter 3), there are multiple factors that can affect occupants' behavioural adaptation in the post-refurbished environment. The study considered factors related to climate (external temperature and humidity), occupants' personal and individual characteristics (e.g. thermal comfort, age), households' economic status (e.g. in regulating indoor comfort), cultural background (e.g. sleeping with the window opened), technological constraints (e.g. occupants' level of availability/accessibility of control over measures) and the ways these factors are interrelated.

A comparison of occupants' comfort levels in the pre and post-refurbishment shows that generally occupants' comfort in the RfF properties has significantly improved in all cases as none of the occupants reported poor comfort levels (Figure 108). Occupants' comfort levels in the RfF properties as reported on the day of the interview were triangulated with the on-site spot check measurements on the same day and evaluated in relation to the temperature measurements from physical monitoring for cold and warm months.

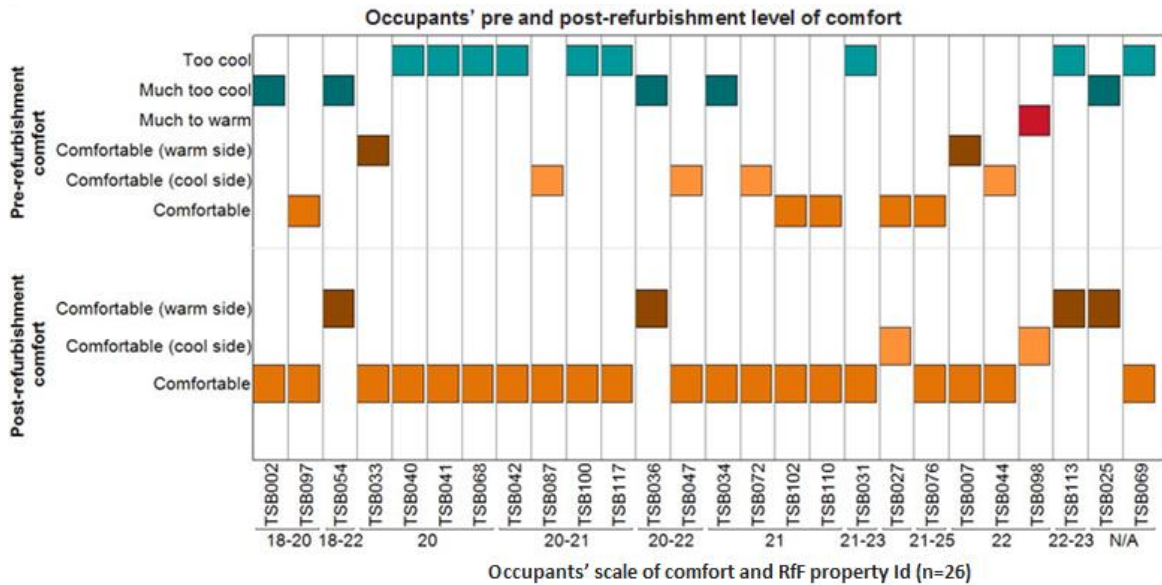


Figure 108: Occupants' rating of thermal sensation in pre and post-refurbishment properties and their scale of comfort in °C (n=26).

In more than half of the cases (n=15) occupants have scaled their comfort level between 18°C and 21°C; whereas in the rest of cases this ranges from 20°C to 25°C (Figure 108). This includes a few cases (TSB025, 068, 069, 110 and 100) in which occupants' heating post-experience and comfort satisfaction were constrained by malfunctioning of the heating system or controls, rendering it difficult for them to define and scale their comfort level:

[female] ...with everything working I would say this house, it's definitely comfortable. I wouldn't say it's much too warm or cold ...[male] I would personally say it's too warm but you can feel the heat properly as you should do, you know what I mean ... (Occ. TSB100).

The mean apparent temperature (AT) that was calculated to measure occupants' thermal sensation in the indoor conditions was examined in relation to how occupants have defined their comfort and actual mean temperature from the spot check measurements on the day of the interview.

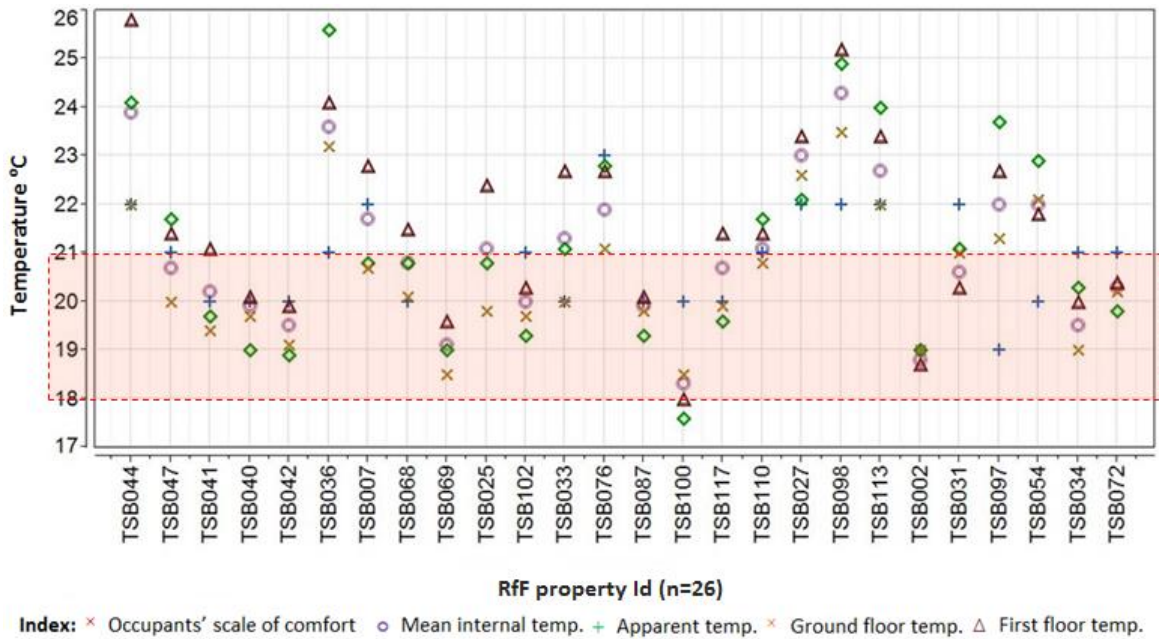


Figure 109: Spot check measurements of mean internal temperature, AT and occupants' thermal comfort temperature in TSB properties (n=26).

Occupants in the sample were generally found to have a mixed understanding of their comfort level during the heating months. In this respect in ten of 24 cases where occupants have scaled their comfort level, this was close to the mean temperature measured; only in five cases was their response consistent with the apparent mean temperature, while in three cases the response was close to both temperatures and in six with none (Figure 109). In almost half of the cases (n=12) occupants' perceived comfort level was found to be lower than the actual indoor temperature and higher in the other half. Hence, like in case of TSB034, occupants scaled their comfort level to 21°C when the actual mean temperature was 18.8°C, whereas in cases like TSB044 occupants' comfort was at 22°C and the actual mean temperature was almost 2 degrees higher. Differences above 1 degree Celsius between the reported comfort level and the actual indoor temperature were found only in five cases (TSB033, 036, 044, 097 and 098).

Temperature variation was found between floors in the majority of the properties, with eight of 26 properties on the ground floor and sixteen in the first floor being above the comfort and wellbeing standards of 21°C (Figure 110).

In these cases the high temperatures on the 1st floor (cross-checked both in on-site measurements and TSB monitoring data) confirm occupants' sayings about night zone overheating, particularly in warm months. In the rest of the cases the lower temperatures (below 21 degrees) of the upstairs sleeping area are mainly due to occupants' comfort preferences for sleeping in a cooler environment, having the window slightly open throughout the year and the TRVs off. Only in two cases (TSB100 and 002) is there a small variation between floors and the sleeping area temperature is at the recommended 18°C of the comfort standards. No significant temperature variations were found between rooms except where the kitchen had possible lower or higher temperatures compared to the other rooms in living zone, related to window operation practices like those related to cooking.

During warm months high internal temperatures were found in households with long occupancy (cluster: 24 hours occupied, cross-checked data from on-site spot checks and temperature monitor loggers) (Appendix 29, Figure 249). Similarly in this cluster temperatures in the living zone considerably exceeded the threshold standards of 21°C during cold months; despite the drop of temperature in the night zone this is again above the recommended 18 degrees Celsius for heating cold months period (Appendix 30, Figure 250).

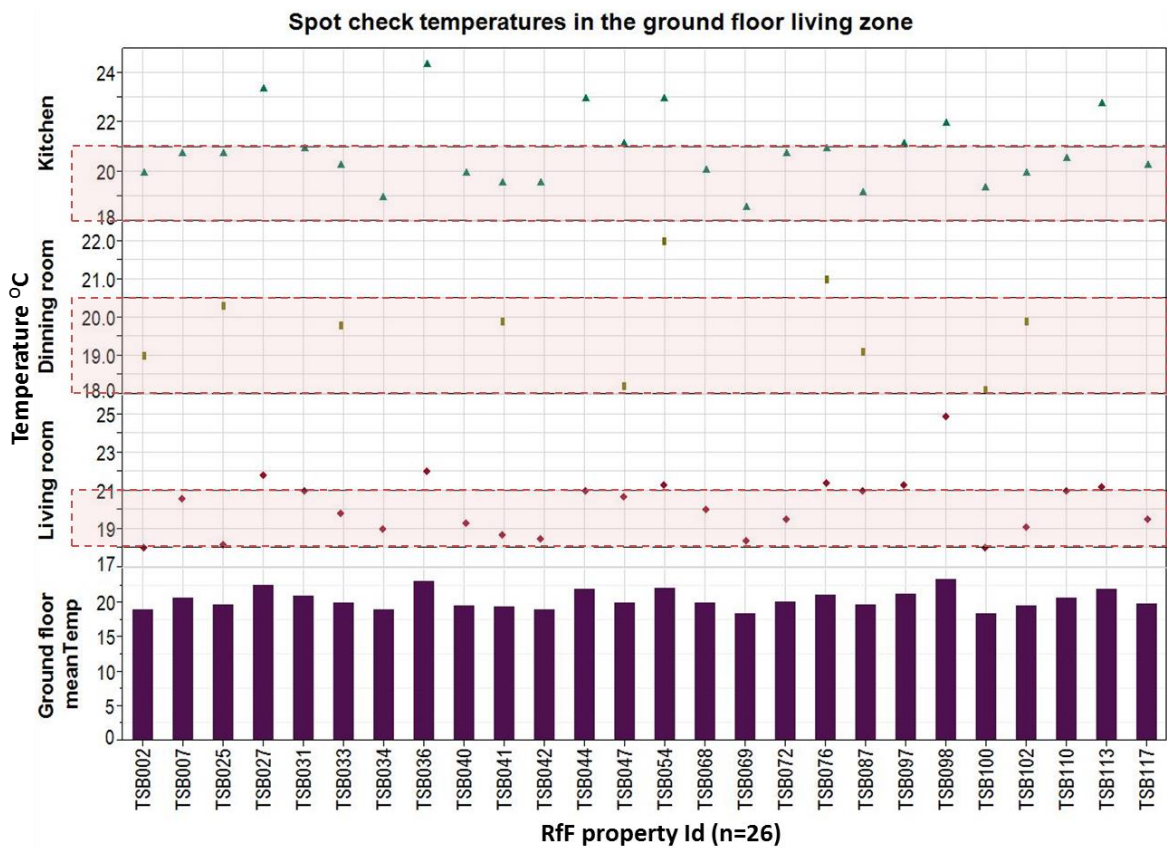
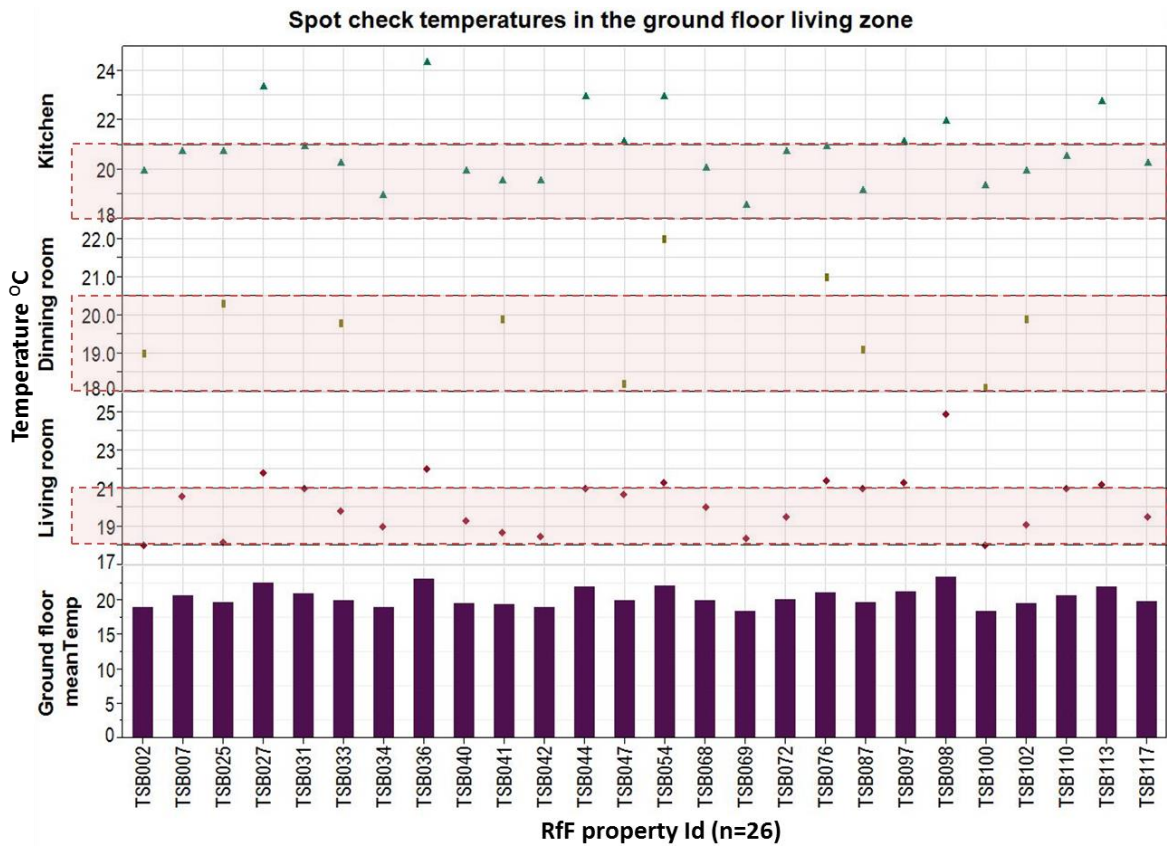


Figure 110: Variation of indoor temperature between floors (spot check measurements).

Correlated factors in this occupancy cluster (n=4) are health issues related also to occupants' occupation status (not working). Except in one case (TSB036) in this cluster with a conventional programmer, in all cases the main heating control is via a Wattbox controller. As can be seen in temperature graphs only, in the case TSB036 heating controls appear more instantaneous compared to the intelligent controller, which is more adaptive to the external temperature variations and responds less immediately to comfort demands. Again despite the similar demographic, health and occupation characteristics, indoor temperatures with less significant variations above 21°C were found in the 22-24-hour occupied households as well as in the other cases with lower occupancy (18 hours to 12 or less), (Appendix 30, Figure 251 and Figure 252).

From the long-term physical monitoring data minor correlations were found between the high indoor temperatures in cold months (October, November, and December) and the family composition and number of occupants. However, a small drop of temperatures was found only in the first floor night zone in households with a small number of occupants (1 to 2 occupants) when compared with family occupied properties (3 to 7 occupants).

8.6 Physiological adaptations to comfort

Adaptive thermal comfort theoretical approaches revealed physiological parameters in the sample related to the occupants' health status, age and gender. These are correlated with different comfort levels between occupants and frequently with personalised temperatures in the rooms based on their individual comfort preferences. Thus, in 10 out of 26 cases occupants report different comfort levels between family members. In half of these cases (n=5) comfort level divergence is related to gender, with females feeling colder and describing their comfort threshold at higher temperatures than men. Health condition (n=10) and age (e.g. women in menopause, n=3) have also affected individual comfort preferences, whether on the cool or warm side. For instance in the case of TSB54 the male

particularly feels the cold when under medication, while the female feels too hot due to menopause effects. Generally occupants with health conditions like asthma and chest infections, cystic fibrosis, rheumatism and cancer (6 of 13 cases) were found to have a better understanding of regulating their thermal comfort. Hence, their comfort sensation was consistent with the actual mean internal temperature, varying from a minimum of 18.8°C to a maximum of 21.7°C, and was largely in accordance with the recommended health and wellbeing standards for comfort⁵³ (Figure 111).

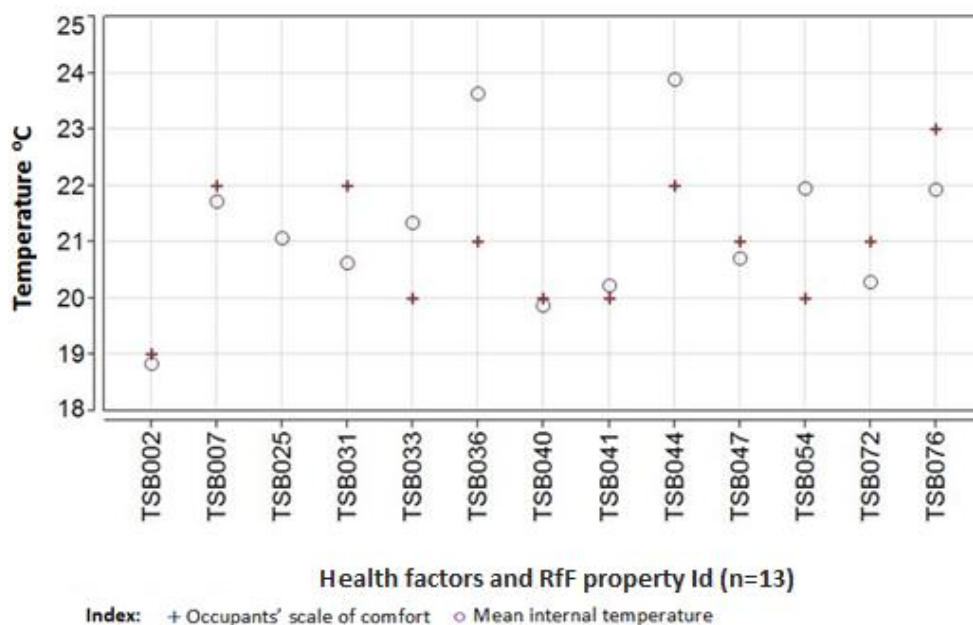


Figure 111: Spot check measurements of mean internal temperature, occupants' perception of their thermal comfort and health factors in TSB properties (n=13).

Mean internal temperatures and occupants' thermal sensations were also examined together with occupants' age. To a large extent in age groups of 18 to 30', 50 to 65 and 65 plus, occupants' comfort sensations and indoor mean temperature are within comfort threshold standards. In most of the cases no significant temperature variations were found between floors except for the group above 65, in which night zone temperatures exceed 21 degrees Celsius (Appendix 31, Figure 253). Therefore, in cases like TSB047, in the post-

⁵³ As discussed in section 5.2.3.2, a comfortable indoor temperature for heated rooms was suggested as being between 18°C and 21°C (referring to 18°C for the night zone and 21°C for the day zone).

refurbishment environment the comfort preferences and indoor temperatures changed to higher temperatures, especially in the first floor bedrooms. This is in spite of occupants' levels of tolerance to cooler indoor conditions before the refurbishment works, which have been explained as:

...don't forget we were both brought up in the war ...you know we only had coal fires and things like that... never heating in the bedrooms or anything like that ...
(Occup. TSB047)

High thermal comfort preferences and indoor temperatures in the sample were found in the 30-50s age group. In eight of 14 cases in this group mean temperatures were above 21°C and considerably high again in the first floor night zone. Children's comfort levels had no significant influence on the indoor temperatures as parental expectations of what is appropriate for their children, was the main factor to determine indoor thermal preferences. Uniquely in the case of TSB036, two of the children have different comfort preferences from the rest of the family, each of them using different practices to satisfy their comfort levels (one has the window open and the other uses additional heaters). Nevertheless, even in cases like TSB098, with a baby below one year of age, the increased temperature up to 24.3°C reflects mainly adults' comfort levels other than babies' wellbeing requirements.

8.6.1 Behavioural adaptations

Occupants' adaptation to the new environment is related to their past-experiences and practices to regulate their indoor comfort. Factors like age and households' income were also examined from a behavioural adaptation perspective in relation to the mean internal temperatures and occupants' thermal sensation. Aspects of the first research question related to the type and frequency of occupants' interactions for comfort are examined in relation to their behavioural changes pre and post-refurbishment in practices to warm up

and cool down. Technological constraints that affect interaction with the low-carbon measures and interrelated factors are also presented in this section.

A strong relationship was found among indoor temperature, occupants' thermal comfort and households' income. Both thermal comfort preferences and actual indoor temperatures are within standards in lower income bands (£0 to £19,999) in twelve out of 14 cases including occupants from all age groups (Figure 112).

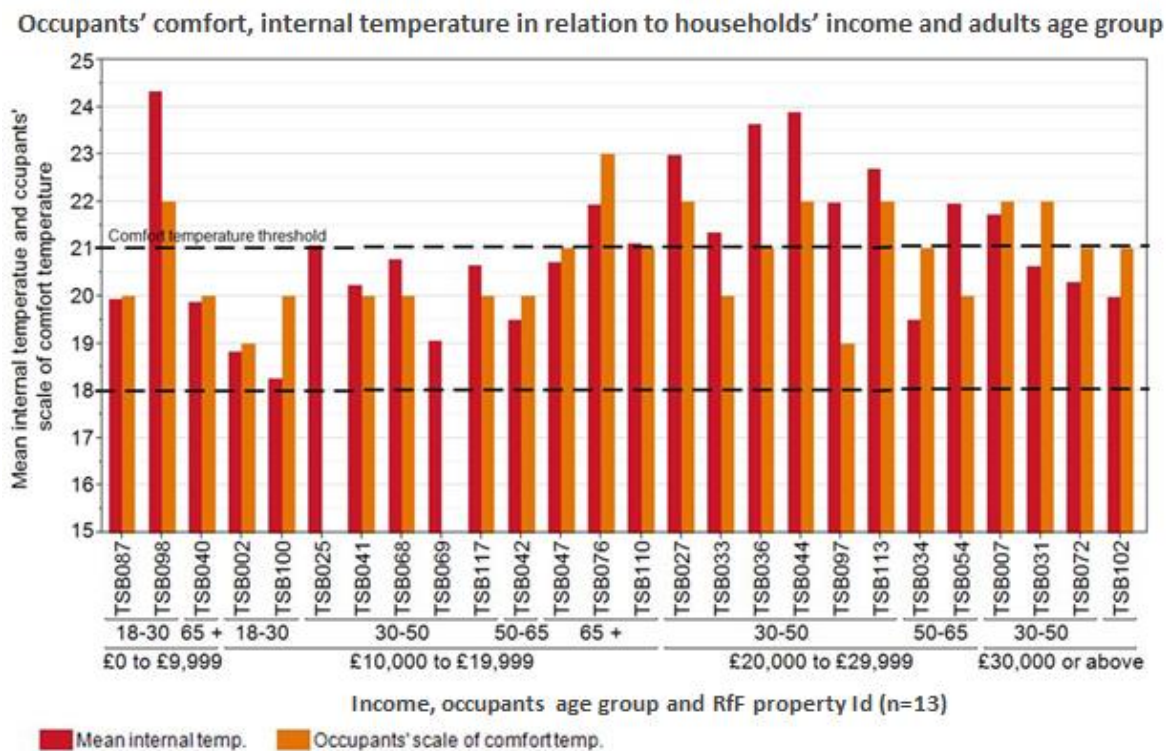


Figure 112: Occupants' thermal comfort and mean indoor temperatures in relation to age group and households' income.

An increase of indoor temperature above standards appears in the higher economic band (£20,000 to £29,999) in 7 out of 8 cases which are occupied merely by those aged from 30 to 65. However, it is interesting to note that in households with income above £30,000 despite occupants reporting higher levels of comfort the actual indoor temperatures are within standards. As discussed in the literature review, a relationship between indoor temperatures and household income has been reported in previous studies. However, with

a small sample size (n=26) of social housing and given the framework of the RfF competition, caution must be applied, as the empirical findings from this study might not be transferable to other refurbishment cases.

8.6.2 Heating practices to regulate comfort

Generally occupants were found to be more susceptible to changing their warm up routines compared to the cool down (Figure 113 and Figure 114). There is only a small number of cases in the sample (2 of 26), in which occupants have changed both cooling and heating practices to achieve their comfort levels in the post-refurbished building. In these cases common practices like opening the windows or turning the heating on, which were previously constrained by the poor building fabric or security issues, are now changed due to the technical interventions after refurbishment.

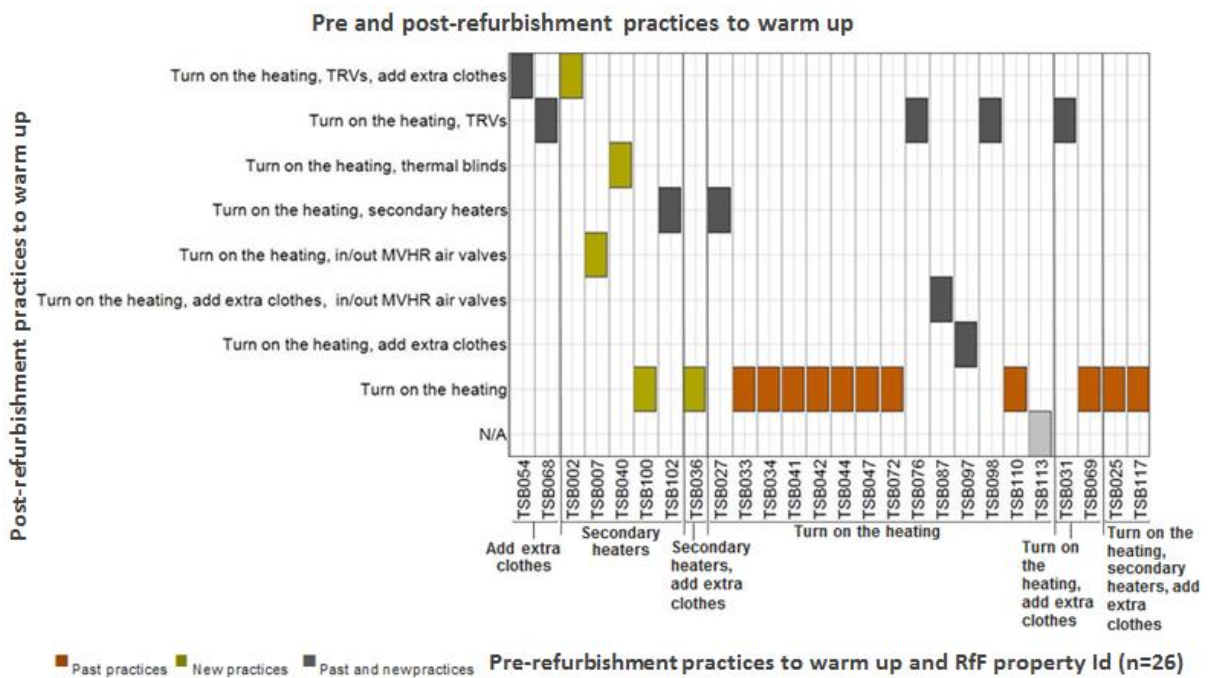


Figure 113: Pre and post-refurbishment occupants’ practices to warm up (n=26).

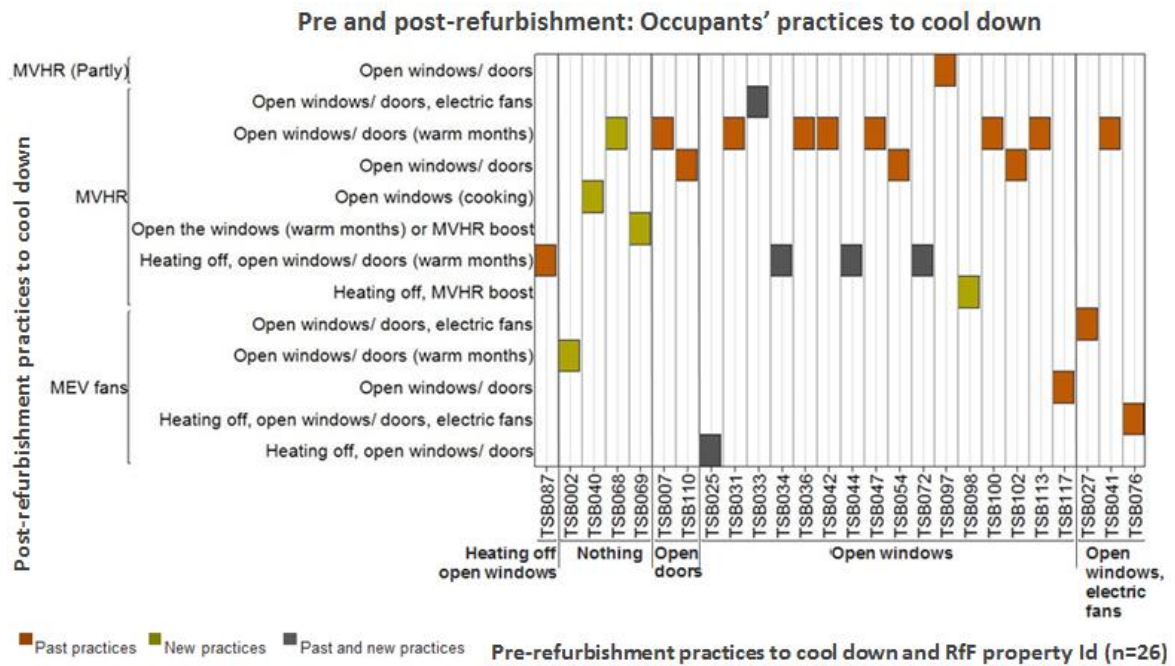


Figure 114: Pre and post-refurbishment occupants' practices to cool down (n=26).

Occupants in eleven of 26 cases in the post-refurbished building repeat common previous heating practices by turning on the heating systems. In contrast, in 3 cases in which occupants in the pre-refurbishment stage used to take additional actions, like using secondary heating sources and adding extra layers of clothing, such practices in the new building environment are now rarely repeated (Figure 113). Occupants' comfort adaptation is related to past-experiences only in a couple of cases like TSB054, in which they were made conscious of adding extra layers of clothes when this is required instead of turning up the heating.

In more than half of the cases (n=14) the improved building fabric and the new heating systems have a significant impact, allowing combinations of previous and new heating practices (9 of 26 cases) or adaptation of merely new actions like controlling heating by the TRVs, thermal blinds or MVHR air valves. Contrary to the expectations of the RfF competition, in a small number of cases (n=2) the study has found occupants still using secondary heaters additional to the main heating. Like in the case of TSB102, the peaks

and drops in temperature levels and humidity as seen in Figure 254 (Appendix 32), confirm occupants' sayings of a lack in heating controls over the communal boiler. In this case previous practices using secondary electric heaters are repeated, with some of the windows opened all the time during cold months.

Occupants' self-reporting on their level of energy efficiency awareness (discussed in previous sections, Figure 97: p.292 and Figure 98: p.294) was found post-refurbishment to often not be in accordance with their heating and cooling practices and households' changes in energy bills. Passive thermal regulatory routines like adding extra clothing may have been replaced by other practices (e.g. like turning on the heating regardless of the self-reported level of energy behaviour (varying from poor and mixed to good), driven by the reduction of energy bills in all these cases (e.g. TSB068, 069, 025 and 117). On the contrary, energy conservation practices have become a new routine for others, with mixed energy efficiency awareness and effects in energy bill change (e.g. an increase for TSB097 and a decrease for TSB002 and 087). Such issues indicate that often the effectiveness of occupants' energy behaviour practices are strongly related with the technology and also with the level of interaction scripted from the measure (e.g. scripted by the technology temperature settings of Wattbox controller compared to conventional programmer).

8.6.3 Level of interaction with heating controls

Except for two cases (TSB068 and 027), in which one of the adults (male) was the main person to deal with the heating controls, no different roles in heating controls were found between household members, with all occupants in the sample having a similar level of interaction with the heating measures. During the POE walkthrough occupants demonstrated and discussed their interaction with direct controls on the heating system like those on the boiler unit and indirect ones like the intelligent controllers (Wattbox and Optima Design Controller), programmers, thermostats, and radiators (TRVs) or storage

heater controls (Appendix 22, Figure 188 to Figure 205). In terms of behavioural adaptation and controls, occupants were asked to scale the level of difficulty in using the heating controls in the post- refurbishment properties. On a scale of 1 (difficult to use) to 4 (easy to use),⁵⁴ almost half of the occupants (n=14) have found heating controls easy to use. However, in the rest of the cases (n=12) occupants have mixed views of the usage of the heating controls, finding some aspects of the measures relatively easy and others difficult in use. Occupants have also evaluated the level of control they have over heating measures on a scale of 1 (full control) to 5 (no control).⁵⁵

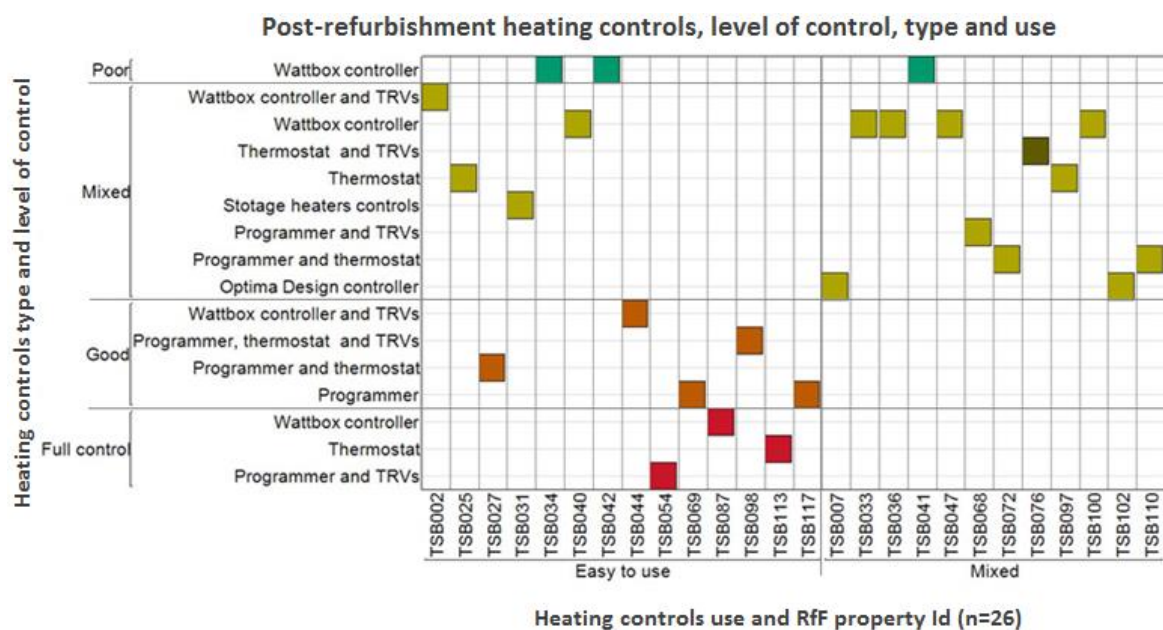


Figure 115: Post-refurbishment heating controls, level of control type and use (n=26).

Occupants' interaction in terms of usage was found to be strongly related to their previous experience with controls. Occupants' interaction with conventional heating controls like programmers and thermostats is often related to their past-experience and know-how with similar measures. In seven out of 12 cases with conventional controls occupants found the usage easy, having full interaction over the measure. For instance, in cases TSB054 and

⁵⁴ Scale difficulty in use of heating controls: 1=Difficult to use, 2=Mixed, 3=Indifferent, 4=Easy to use.

⁵⁵ Scale of the level of control occupants have over heating systems' controls: 1=Full control, 2=Good, 3=Mixed, 4=Poor, 5=No control.

113, occupants' interaction with conventional controls involved setting up the programmer and arranging their preferences according to their occupancy times and temperature comfort levels (Figure 115). In contrast, in the rest of the cases (5 of 12) occupants have mixed usage by partly controlling the measure. In these latter cases (TSB072, 110, 076, 097 and 068) occupants have no interaction with the programmer as it is set on the default option. However, they are active only by increasing (or decreasing) the temperature from either the programmer or thermostat manually using the same practices they used with similar controls in the past-experience. No direct interaction was found with the system's controls (controls on the boiler unit) in the cases of biomass, heat pumps, and micro-CHP boilers (14 of 15 cases) as it was designed for passive users and initially scripted from the measure for not to involve interaction. There is only in one case did occupants have both mixed interaction by taking action and rebooting the heat pump system from the boiler's controls when the system was not responding.

A new experience for all occupants with intelligent controls was their interaction with Wattbox or Optima Design Controller. Only in two out of 13 cases did occupants find it easy to use the measure, with either full or good control over the heating system (Figure 115). Although occupants in some cases (n=4) describe the intelligent controls as easy to use, their actual interaction is either mixed (some level of control but not entire) or poor. Similarly in these later cases together with the cases (n=7) with mixed usage, the level of interaction with the intelligent controls has been explained by the occupants as a technical barrier in the installation of the controls and not conceived as 'closed' scripted controls of the system itself. This aspect has also affected the frequency of interaction with the Wattbox controller given that control options do not allow instantaneous temperature changes as discussed in Section 8.4, page 315. This issue was also related to Wattbox's scripted options for occupancy limiting occupants' comfort adaptivity and controls. The

level of prescribed control over the measure, together with installation aspects, the type of instructions occupants had (information with no demonstration) and insufficient control left to the users, has made the majority of the occupants in the sample passive with this type of heating control, and with a mixed to poor level interaction. In this respect occupants' sayings of their experience and use of intelligent or conventional heating controls were compared with the indoor temperature variations in living and night zone rooms for the month of October. For instance, in the case of conventional controls like in TSB069, temperature variations confirm occupants' sayings for setting up the programmer according to their occupancy schedule; but in the case of TSB054, except for the programmer settings occupants used to regulate their comfort preferences by using manually the thermostat, especially in the case of visitors on weekends (Appendix 33, Figure 255). In properties with Wattbox intelligent controls there is a difference in temperature variation when controls communicate properly with the heating system, like for instance in case TSB036, with those that do not, like cases TSB034, 040, 041, 047, etc. (Appendix 34, Figure 256 to Figure 262). Except for the malfunction of the system in these latter cases, the graphs also entail occupants' sayings of trying to implement instantaneous heating controls on the intelligent controller as in previous experience. Therefore in these cases there is often a strong variation of temperature peaks and drops with fragmented patterns. In other cases like TSB041, although the intelligent controller was adapted mostly during the weekdays to occupants' occupancy schedules on the weekends, there is occupant demand for less heat (Appendix 34, Figure 258).

As expected, the gas consumption graphs show that for the same period (year 2011) the heating period for each household varies by a month or two depending on occupants' different comfort levels. Therefore for instance in case TSB054 the heating is turned OFF from April to September (confirming occupants' sayings), whereas for TSB025 this occurs

from May to August and for TSB027 from end-June to mid-September (Appendix 34, Figure 261).

Occupants' past-experience and previous practices to regulate room temperature through TRVs and storage heater controls were generally very limited due to the obsolete technology and lack of controls of the pre-refurbished heating systems. To a great extent (11 of 21 cases) when occupants' adaptive behaviour is not 'scripted' by the measure the frequency of interaction with TRVs was found to be only comfort and season dependent. In these cases TRVs controls are set to different temperatures varying between rooms and floors depending on occupants' temperature preferences. In this respect, comfort and cultural factors affected interaction by keeping bedroom radiators turned off (e.g. TSB069, 054 and 47), bathrooms radiator valves at the highest temperature level, or keeping for instance radiators in the non-occupied rooms off based on the level of awareness and engagement occupants have over energy conservation. In three cases users' mixed (active/passive) interaction with the TRV controls was either due to the design strategy (e.g. in case TSB036 TRV controls existed only in bedrooms) or due to the level of information/training provided (e.g. for TSB072 and 031 there was insufficient information on the remote TRVs and storage heater controls). In the rest of the cases (n=9) occupants were generally passive, having very limited to no interaction with the measure and the thermostatic valves that were mostly left turned on at higher levels.

Similar to the space heating usage of controls was occupants' direct and indirect level of interaction with the hot water controls, whether these were via boiler, programmer, intelligent controller or individual solar thermal panels' controls (Appendix 19, Table 24).

Generally, from the physical data and occupants' statements it appears that although both conventional (programmer and thermostat) and intelligent heating controls (Wattbox and

Optima Design Controller) were designed for active users, occupants have mostly mixed control and are active in consciously regulating and operating heating systems controls when operation is not scripted by the measure (e.g. scripted by installations failures and malfunction of the system or by the technology itself). Overall there is a strong link and repetition of previous practices in heating controls for regulating occupants' comfort, whether this was to warm up or cool down the indoor environment. This clearly implies that some of their practices are robust against major changes and interaction with new intelligent systems. Occupants found intelligent controls that automatically detect and learn occupants comfort preferences from their occupancy routine repetition frustrating mainly for the system's inability to allow them interaction for temporary temperature adjustments.

8.6.4 Air quality comfort conditions and ventilation controls

The air quality of the indoor environment is generally provided through natural ventilation by window and door openings and by mechanical ventilation via MVHR or MEV systems installed in all rooms or merely in wet rooms (kitchen and bathroom). Although operation of windows and doors is traditionally related to ventilation controls, this has a significant impact on heating comfort and controls. Previous common practices to cool down the indoor environment mainly included windows and doors opening, with only a few cases (n=4) of also taking other actions such as turning off the heating or turning on electric ventilation fans (Figure 116). In a few cases (n=4) occupants' adaptive behaviour involved new practices like opening windows and doors; in the poor pre-refurbished buildings such actions were not allowed as the indoor environment was constantly cool. It is interesting to note that only in 1 of 26 cases had occupants' previous practices involved turning off the heating before opening the windows and even in the post-refurbishment stage such cases still remain very few (n=4).

Despite the mechanical ventilation systems⁵⁶ installed in the refurbished buildings, occupants' most common practice to cool down remains opening windows and doors, or even like in the case of TSB033, using electric ventilation fans. Most practices involve opening windows throughout the year, in specific seasons or related to everyday routines like cooking, sleeping, and bathing, etc. Ventilation practices involved a combination of window opening and the use of electric ventilation fans, MVHR and heating controls in a large number of cases (n=10).

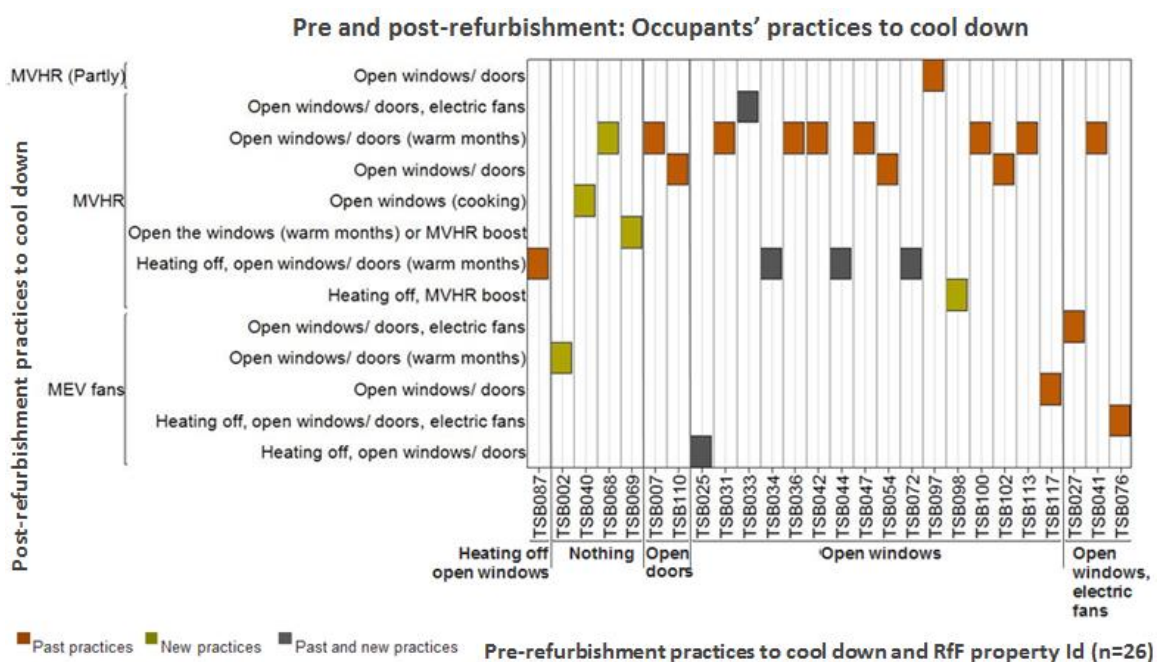


Figure 116: Pre and post-refurbishment occupants' practices to cool down (n=26).

In sixteen cases occupants' behaviour in windows' operation during the cold months⁵⁷ has changed. In some cases (n=5) with MVHR systems installed, previous practices involving leaving all windows open for the whole day or opening them once a day for some hours

⁵⁶ The MVHR's performance efficiency is reduced when there is a continued opening of windows as it affects the system's ability to keep the building warm in the cold months and cool in the warm months. According to system specifications opening of windows is recommended only during unusually high temperatures. The 'summer purge' is however the standard practice in hot climates and involves open windows during the night time to allow cool air to enter indoors to reduce indoor temperatures, as well as keeping windows closed during the daytime and increasing ventilation only by the fan speed in the control panel.

⁵⁷ This considers the cold months for heating and warm months for cooling demand (e.g. for the UK heating season from January to March and October to December, DECC 2013).

now have changed to opening some windows merely for several hours. Prior practices of never opening any window due to the considerably poor building condition in pre-refurbishment have changed to opening some windows for less or more time throughout the day.

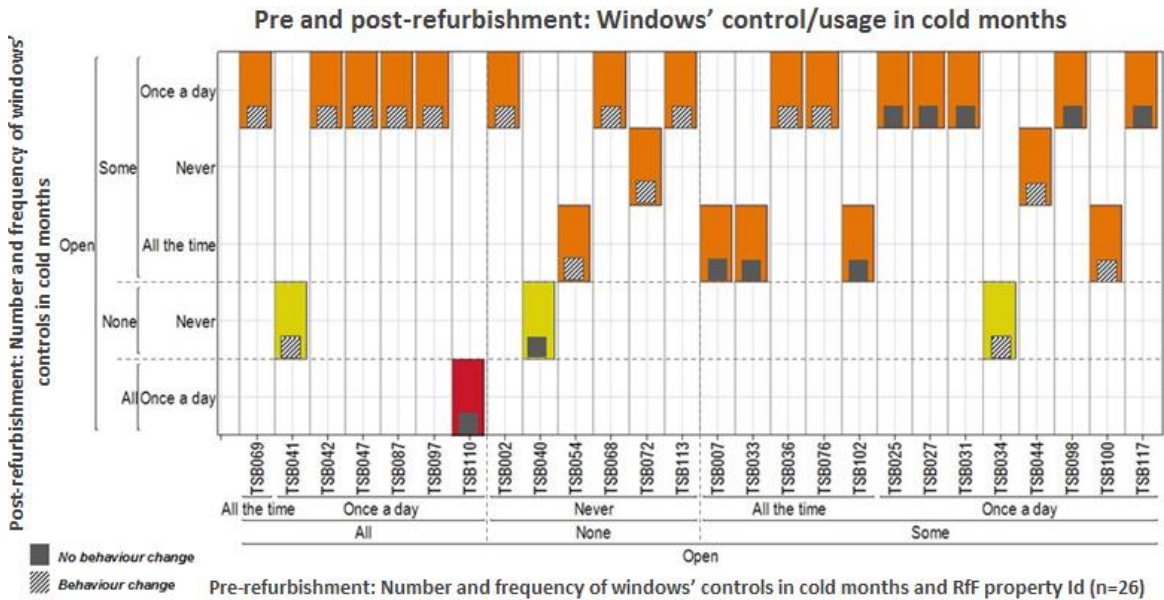


Figure 117: Pre and post-refurbishment practices: Windows' controls and frequency of use in cold months (n=26).

Behaviour changes related to the building environment like in the case of TSB054 were often explained as cultural issues:

...it's how I grew up... [sleeping with the window open] (Occup. TSB054)

Therefore, occupants' past-experience habits of routinely opening windows to regulate their comfort levels, like in cases TSB054, 007, 033 and 102, are consciously repeated in the post-refurbished experience, again leaving bedrooms' windows slightly open all the time even overnight along with the MVHR system (Appendix 33, Figure 255 to Figure 258). There is only one case (TSB110) in which the new low-carbon systems have had no impact on changing previous practices in either warmer or cooler seasons (Appendix 35). And in one case (TSB034) the MVHR technology had a significant impact on occupants'

adaptive behaviour change. On the contrary, in cases like TSB041, despite occupants' sayings of never opening the windows during cold months due to MVHR technology, the physical data show some instant humidity increase with a temperature and CO₂ drop indicating interaction with windows (Appendix 34, Figure 258). As Figure 117 shows, the number of cases with MVHR systems that have all or some windows open all the time throughout the day is generally small (n=6).

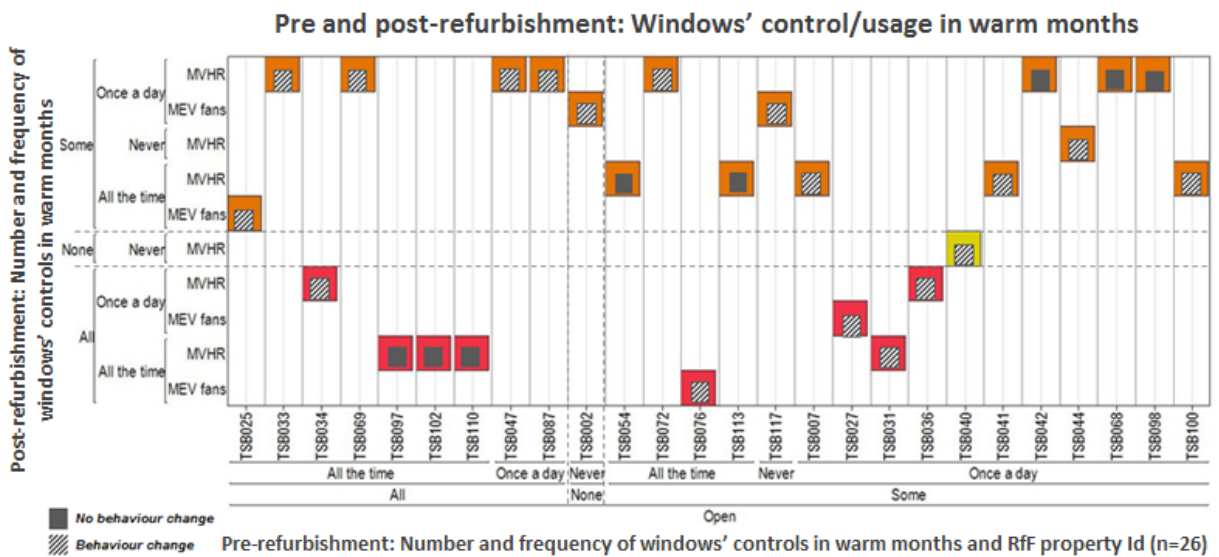


Figure 118: Pre and post-refurbishment practices: Windows' controls and frequency of use in warm months (n=26).

In the warm months occupants' interaction with windows operation has changed post-refurbishment in eighteen cases (Figure 118 above). Previous practices with some or all windows opened all day are repeated in a small number of cases (n=5) regardless of the air supply from the MVHR system (Appendix 35, Figure 265 and Figure 266). Only in one case (TSB040) was occupants' adaptive behaviour following the instructions given for the MVHR system to not open the windows in either warmer or cooler months. Comfort adaptation and controls in all properties follow weather variations, with occupants opening windows and patio doors during warmer days, whereas in other properties window

operation is constrained by security and privacy factors like in cases TSB 033, 036, 100 and 072.

Generally occupants' post-experience in opening windows at least once a day for some hours (in both cold and warm months) was also found to be related with cultural values and routinised habits. Therefore, in the living and sleeping areas windows are opened for a certain time for airing whereas in practices of cooking or bathing all occupants, despite the mechanical ventilation systems (MVHR or MEV), tend to have the windows open during or after their activities. In this respect the frequency of window control varies throughout the house, dependent on the activity that is taking place in the room. Although indirect ventilation measures like windows' trickle vents are installed for active users (e.g. interaction by opening and closing the window's trickle vent) in eight properties, in none of these cases did occupants have interaction with them. In some cases like TSB102 having all windows open during warm months cannot be seen only as a repetitive behaviour of windows' control but also as occupants' adaptive behaviour to the building's overheating, especially in the first floors during warm months, confirming occupants sayings (Appendix 32, Figure 254).

As regards the doors' control, in more than half of the cases (15 of 26) no significant changes were found from previous practices (Figure 119 below). In these cases all or some doors are kept closed for some hours, involving practices of sleeping or cooking. The interactions identified in door control show that occupants in more than half of the cases (n=17) tend to be active with door operation post-refurbishment, due more to privacy factors than to heat conservation in the rooms (Figure 120 based on Table 26, Appendix 28).

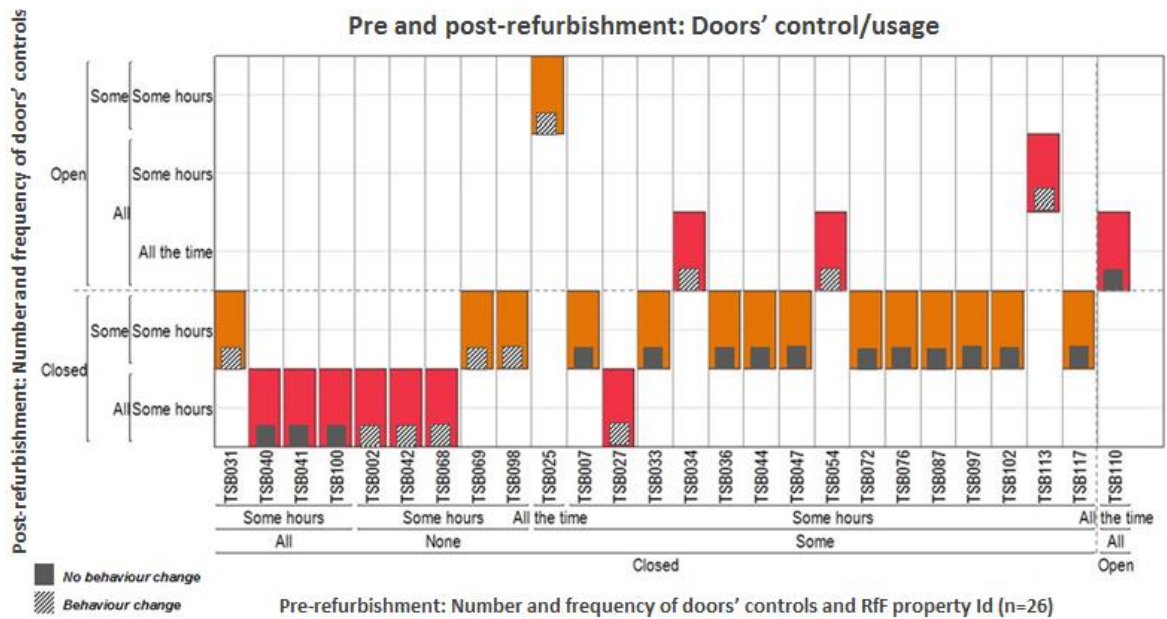


Figure 119: Pre and post-refurbishment practices: Doors' controls and frequency of use (n=26).

Similarly to previous windows operation, improved building condition after refurbishment allowed occupants in a couple of cases to keep all doors opened all the time, rather than keeping them closed as in previous building environment practices. In these cases often occupants keep the doors open in all rooms - heated or non-heated and even in those not used - due to physiological and behavioural factors or to occupants' age (e.g. young children, teenagers). A different example that prescribes users' comfort controls and physiological adaptation, determining the level of their passive/active interaction with doors, was found in case TSB036. Here occupants are constrained to keep doors open at night as the MVHR has an indirect effect over the doors (when doors are shut they tend to bang from the air flow created in the room by the mechanical ventilation), influencing occupants' sleeping practices. Occupants were dissatisfied as they have no interaction or control over passive measures like doors' lower edge undercut gap. Except for the kitchen door, due to cooking practices, the frequency of interaction in the use of doors was found to be minor.

Again factors that were found to affect and prescribe occupants' interaction with both passive and active ventilation controls are the design and the technology of the product.

The figures below (Figure 120 and

Figure 121), show that to great extent occupants have full control over the natural ventilation measures by opening and shutting windows and doors according to their comfort preference, when systems' operation is not scripted.

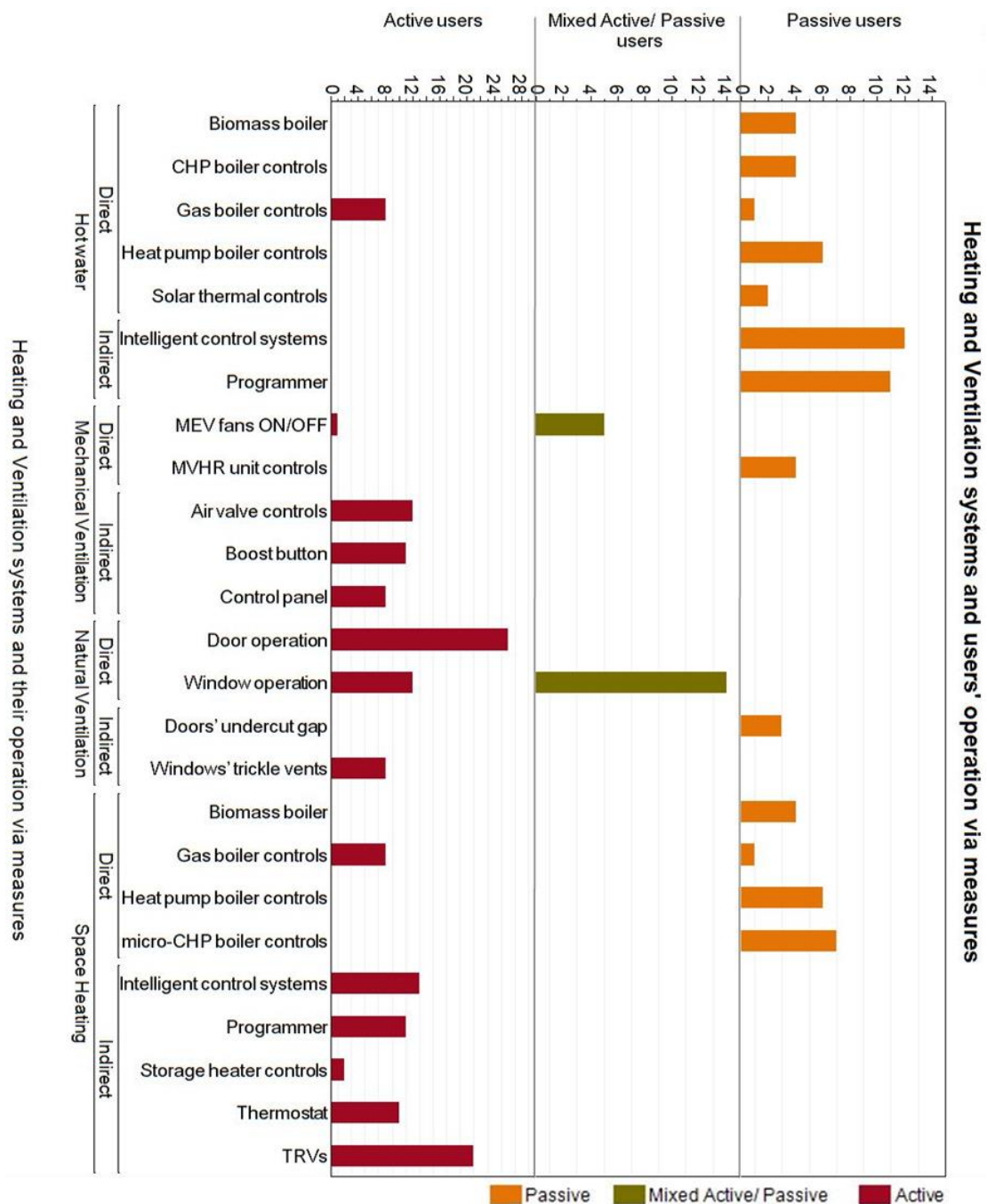


Figure 120: Heating and Ventilation systems and users' operation via measures (n=26 properties).

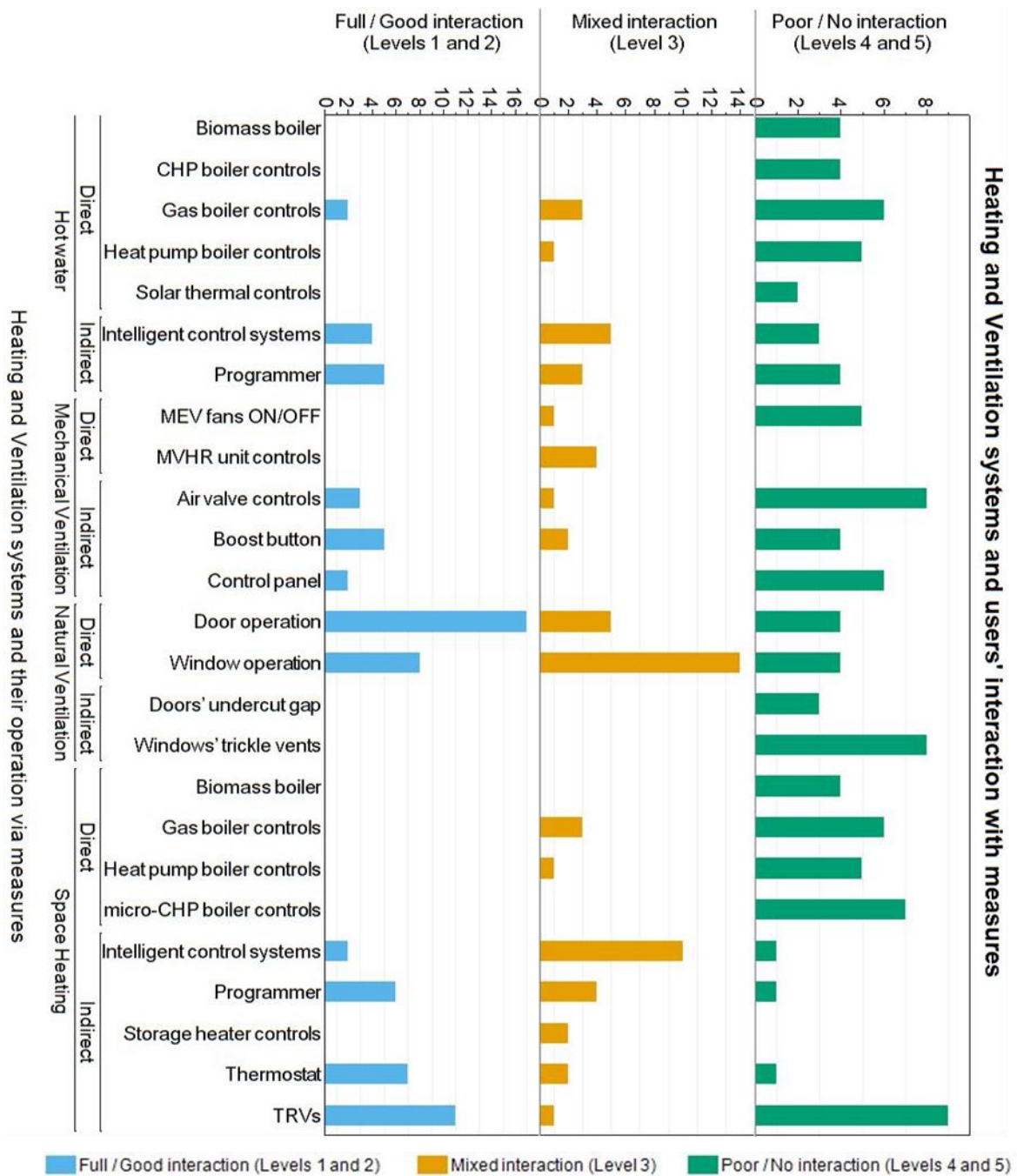


Figure 121: Heating and Ventilation systems and users' interaction with measures.

However, there were also cases (n=14) (as discussed in section 8.4, page 315) where some of the windows installed have constrained full operation of the measure, rendering mixed interaction with it. Another related factor affecting occupants' interaction was the lack of design participation and choice they had over the improvements having a significant impact on how windows were operated. The size of the windows (e.g. too big), the type of

the opening (e.g. tilt, pivot) and the opening direction (e.g. inwards, outwards) were scripted factors that limited or prevented full control.

The mechanical ventilation with heat recovery systems were designed to supply air to the long occupied rooms like the living room, dining room and bedroom, and exhaust the air from the wet rooms like the kitchen and bathrooms. Generally, no interaction or poor occupant interaction with MVHR controls was found even in cases when control is provided and although full operation is scripted by the measure (e.g. filters type, control panel options). Occupants had very little control over the MVHR control panel (2 out of 8 cases). Although controls like the booster fans in the wet rooms (kitchen and bathroom) are generally used by the occupants, in a large number of cases they were found insufficient for the steam and humidity levels from bathing and cooking practices. Like in the case of TSB097, the low temperatures in the kitchen room confirm occupants' sayings for frequently opening the windows due to the insufficiency of the MVHR system installed in the wet rooms to extract room humidity and smells when cooking. In these cases opening windows even in the cold months has been a quite common event of interaction for most occupants. In properties with uneven distribution and intensity of the blown air from the MVHR in some rooms (e.g. cases TSB100 and 007), occupants had to interact with MVHR vents by closing them completely to regulate indoor comfort (Figure 120). Another issue that emerged is that despite the high insulation levels and the MVHR ventilation system installed to circulate cold air during warm months, significantly high temperatures were found in the physical monitoring data for the months of July and August in sixteen cases (Appendix 36, Figure 267) often with unexpected results of overheating.

The interaction with the windows is directly linked with the MVHR operation, and as discussed is determined by occupants' physiological comfort, behavioural adaptation and

activities in the room to regulate the indoor environment. In all cases occupants' understanding was generally mixed on how to operate windows and the MVHR system in warmer and cooler months; and to some extent this was related to the mixed information/training they had on the new measure. The instructions they received from the project team were reported as 'don't need to touch it', which has prevented some of the occupants from having any type of control over the MVHR fans and made them passive over controls that were designed for active users. Interaction with both measures was found also to be generally affected by other important 'micro' factors related to ventilation prefiguration and occupants' behaviour such as smoking indoors or having pets living in the room, increasing CO₂ levels. This is discussed in the following sections.

a. Natural vs. mechanical ventilation

The empirical data was cross-checked with the physical monitoring measurements to explain the impact of the system on occupants' air quality comfort. The on-site measurements of relative humidity and CO₂ levels in all actively occupied rooms were compared to the UK standards for adequate air quality (BSI and CIBSE indicators). Relative humidity levels were generally found within BSI standards in all cases with no significant variations between zones (living and night zone) or seasons. Variations were found when frequent window operation was involved following occupants' activities like cooking, bathing and sleeping (Appendix 34, Figure 261 and Figure 262).

Variations between floors in CO₂ level were found only in a small number of cases (n=7), with poorest levels in the living zone compared to the night zone. In three of five cases where occupants reported having some windows open all the time in bedrooms, CO₂ fluctuates from normal to below the recommended levels (lower than 800ppm); conversely, there are cases like for instance TSB054 and 102 in which CO₂ levels are especially high despite the main bedroom windows always remaining open throughout the

day and the MVHR constantly ON. In twelve of 26 cases the poor CO₂ levels (above 1000ppm) found in the kitchen room indicate insufficiency of both MEV and MVHR systems to perform ‘as designed’, together with occupants’ inactivity in operating windows due to installation faults (Appendix 27, Figure 220 - Figure 246).

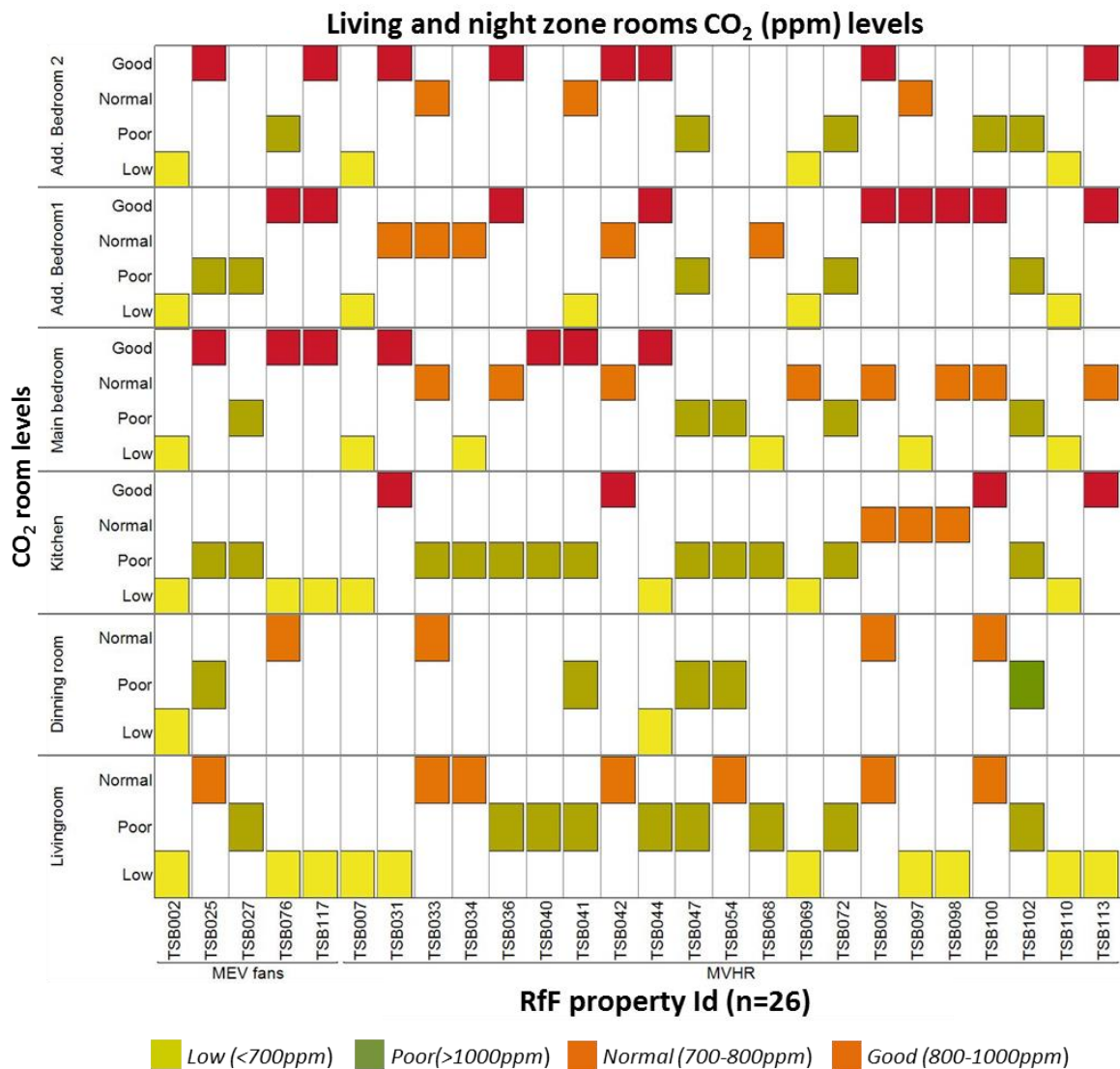


Figure 122: Spot check measurements of CO₂ levels in the living and night zone rooms

In cases with mechanical extract ventilation fans (MEV in five properties) occupants tend to repeat previous natural ventilation practices of opening windows one or more times a day to air the house. The CO₂ levels for these cases vary according the activities that are taking place, with occupancy and other micro factors like indoor smoking habits and pets

increasing levels and affecting frequency of window opening. For instance, in the case of TSB076, with a large number of occupants, four cats living indoors and more than one occupant smoking in the house, high levels of CO₂ were found from the physical monitoring; the CO₂ drop captured from the interview meterings (windows were open before and during the interview spot check carried out in November) is explained by alternate window opening once a day in the high occupancy rooms. The CO₂ levels below 800ppm confirm occupants' sayings of opening windows once a day to air the living space or when cooking.

From the physical data it was found that often occupants' behaviour with the new MVHR ventilation system differs between the first months or year of occupancy and as they get more living experience in the refurbished property. In cases TSB040, 036, 087 and 100 CO₂ levels were initially low, often even below standards, indicating repetition of previous practices in window opening. In these cases CO₂ levels were increased significantly after the first period of occupancy, with occupants showing more adaptive behaviour to the new ventilation system by keeping windows shut (e.g. TSB036, 087, Appendix 36, Figure 272). Likewise, in case TSB100 occupants interacted with the MVHR system by closing the air valves to prevent cold air blowing (Appendix 36, Figure 273). Poor levels above 1000 ppm were also found in cases of TSB044 and 041 with a high number of occupants (4 to 5 occupants) and adaptive behaviour practices to keep windows mainly closed (Appendix 36, Figure 273). In twelve of 16 cases where occupants' practices involve windows being open all the time or once a day, CO₂ was found as expected below standards (800ppm) (e.g. TSB 033, Appendix 36, Figure 274). In the case of TSB034, meanwhile, occupants' sayings of never opening the windows in cold months and only once a day in warm months contradicted the particularly low CO₂ meterings and relative humidity trends that follow external variations (Appendix 36, Figure 275).

Although this data must be interpreted with caution because of the small number of cases (n=26) the findings indicate that factors like mal-operation due to installation, occupants' window opening and MVHR air valves controls, together with occupancy and other micro factors, can significantly affect the measure's performance. These factors may also explain the relatively little variation between the mechanical ventilation systems installed (MEV and MVHR), as the unsatisfactory CO₂ levels (below or above standards) are generally strongly correlated with windows' operation and the overall performance and usage of the mechanical ventilation systems. In this respect the findings suggest that only in a couple of cases was sufficient indoor air quality achieved exclusively by the MVHR system, as natural ventilation practices, to a greater or lesser extent, were generally involved in most cases in the sample.

8.7 Summary of main factors affecting interaction

From the analysis of the empirical data key interrelated factors affecting occupants' interaction with the low-carbon measures emerged. These factors are discussed in this section under the lens of the theories drawn on for the study's conceptual framework (discussed in Chapter 4).

Occupants' past and post-experience was shaped by interactive effects between occupants and the building system. Their past-experience in a poor building environment had a strong impact not only on their comfort levels and energy cost awareness but also on their routinised practices related to heating and ventilation controls. The events of interaction in the pre-refurbished building were mainly scripted by the technology and products, which were directly determined by the building's poor physical condition, systems' type and age as well as by the excessive heating expenses. In this respect such factors have not only determined occupants' physiological and behavioural adaptation in the pre-refurbished stage but also to a great extent made them passive recipients with merely a little control

and interaction. Thus the main reason in keeping high temperatures in the pre-refurbished stage was mainly the presence of young children and visitors.

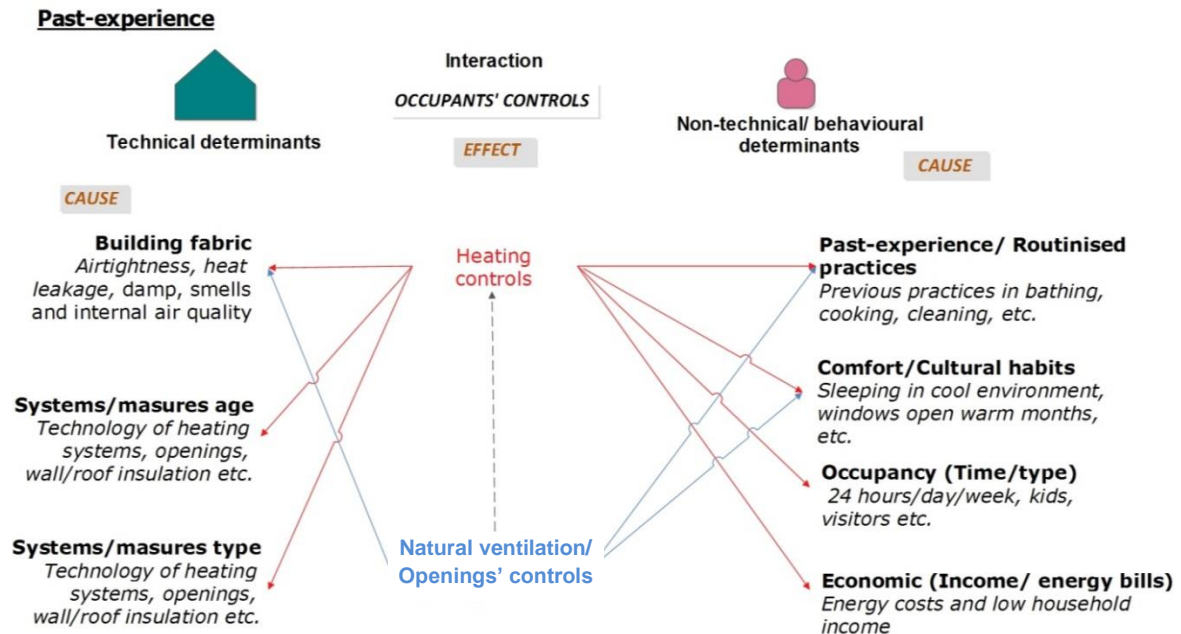


Figure 123: Past-experience causes and effects of interactions.

A comparison of the negative factors that emerged from occupants' past and post-experience in the property (Table 18, p.279, and Table 19, p.287), suggests that although the overall living experience in the refurbished property was significantly improved, some aspects are still prominent to a different extent. Therefore, key factors affecting satisfaction post-refurbishment are technical aspects in design and installation (Figure 123). The previous constraints of the poor building condition are now in the refurbished building environment lack in controls due to scripted technology and installation failures. The low-carbon technology of the building fabric, systems and measures affects occupants' control interaction not only in terms of products' actual scripted factors 'as designed', but also to a great extent by the way these were installed and performed in-use. The design decision of the specific systems installed in some cases has not considered how occupants and their lifestyle (e.g. biomass and manual feeding or Wattbox and occupancy variables) have important implications on their satisfaction and interaction with the

measures. Additionally house location (e.g. rural or urban area) and routinized practices of opening windows were not considered in relation to MVHR system operation and performance.

On the other hand the post-retrofit environment has allowed physiological factors like health and behavioural aspects like personal individual characteristics (e.g. habits) or cultural responses and interaction with the new technology to evolve differently in some respects (Figure 124).

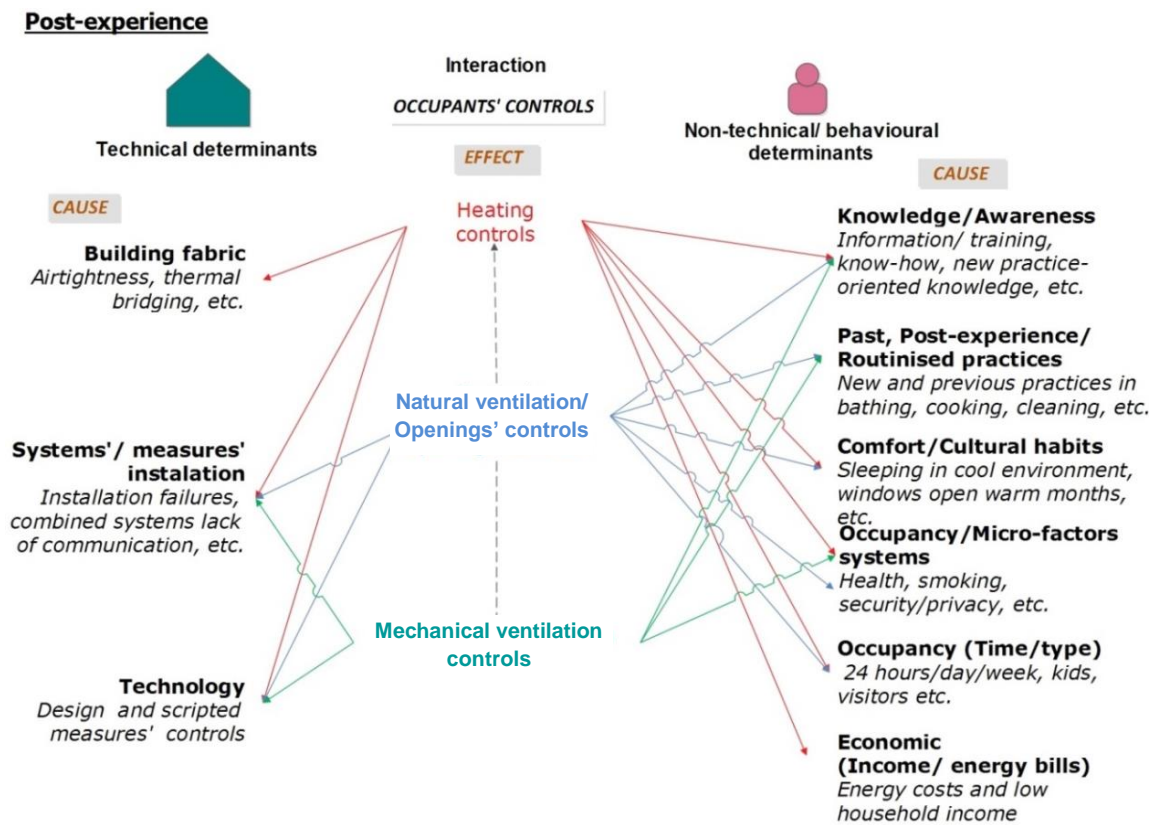


Figure 124: Post-experience causes and effects in occupants' interactions.

For instance, comfort adaptation and indoor internal temperatures are directly correlated with occupants' health condition and time of occupancy, which is also indirectly related to the occupation status of the social tenants, (see Appendix 37 variables correlation mapping). Or there are cases in the sample where buildings' airtight environment now allows occupants to choose their habits and adapt their routines in a more decisive way

compared to their past-experience with operation of heating controls and openings (rebound effect). The low-carbon systems have in part affected previous heating practices, allowing some of the occupants to be active users dealing with an active heating system that responds to their controls and supporting their physiological and behavioural preferences. In contrast, others tend to be passive users dealing with a system that was designed to be active but installed to respond in a mixed active/passive way to their in-use controls and comfort preferences.

Another important factor in occupants' post-experience control related behaviour in heating and ventilation practices is knowledge. Three types of occupants' knowledge emerged from the sample: the knowledge provided by the RfF process through training, information or demonstration of the new measures; the knowledge obtained by occupants' own proactivity and practice-oriented interaction with the measures; and finally the know-how from their past-experience with previous systems and measures. The type of information/training on the low-carbon interventions and the time and the person ('housing officer') who provided it have been important variables strongly correlated to occupants' satisfaction, opinions of the measures and interaction with them. The know-how of regulating heating controls like the TRV valves or the thermostat and programmer involved a transfer of knowledge from past-experiences of interaction with similar technology in some cases, whereas occupants' interaction with intelligent controls or MVHR built up their new experience or know-how with the 'new' low-carbon technologies. The lack of information on how to operate combined systems like windows with the MVHR often goes beyond occupants' 'energy satisfaction' of 'doing the right thing' in terms of energy conservation, that contrasts with routinised practices and habits (e.g. sleeping with windows open). These issues suggest that although occupants can be engaged in regulating indoor air quality, the meaning of the things they do is often

different from the knowledge and technical understanding they have in relation to complex systems.

With regard to heating, occupants are active users both directly (e.g. controls on the boiler unit) and indirectly (e.g. control via TRVs) in positive and negative ways with heating controls when this is allowed by the system. However, when combined systems are not working properly users have either a negative or a mixed interaction and passive behaviour (adaptivity) with measures designed for active users. In natural ventilation occupants have full control and interaction through openings when design faults are not involved, although not with a positive effect on the mechanical ventilation system. Occupants have an indirect influence over mechanical ventilation as active users by interacting with openings; although it was installed and explained to all occupants as a measure for passive users. Eventually the technical failures in installation, along with the lack of systematic information, instruction, and support provided for the systems installed, resulted in occupants having a mixed understanding of it and often a mixed interaction with practices and measures affecting each other. Occupants' post-experience satisfaction levels of living in a low-carbon building were also linked to negative aspects of the refurbishment process (duration and disruption of the works), as well as to the support, maintenance and energy feedback they will get during and after the completion of the RfF competition.

Occupants' expectations were generally set high, correlated not only with the anticipation of significant reduction in energy cost, but also with systems, building and measures installed. The level of decrease or increase they had on energy costs was found to be directly related to their levels of awareness, opinions and finally interaction controls of the new systems. Despite the small size of the sample used in this study a household's income was related to its thermal comfort preferences. With regard to the buildings, although the need for more space may be solved for those households with families, the lack of storage

space due to the low-carbon equipment installed is now an important issue for almost all cases, having an effect on their opinion about deep low-carbon refurbishments.

Figure 125 below, summarises the key points in which occupants' energy behaviour has changed in the transition from pre-refurbishment (past-experience) to post-refurbishment (post-experience). Major changes occurred in aspects related to occupants' comfort behaviour in which from passive users with poor interaction has turned to active users with full/mixed interaction; in this respect their satisfaction levels with the building environment has also been positively affected.

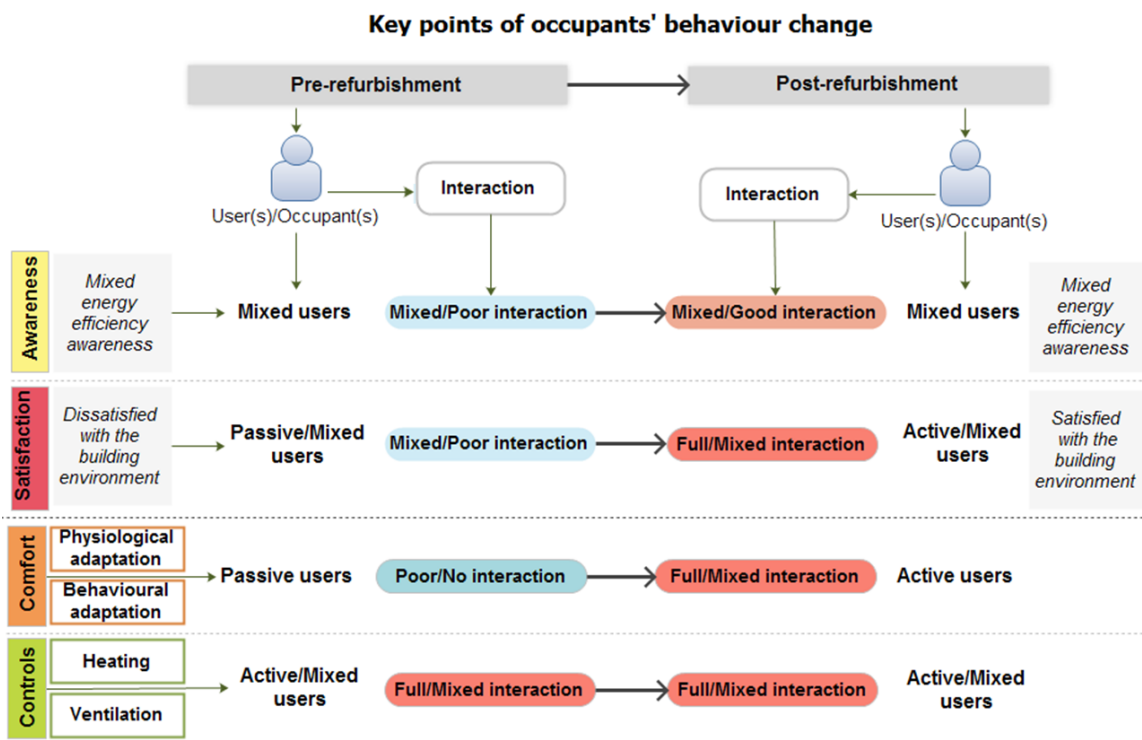


Figure 125: Key points of behaviour change transition emerged from the RfF sample.

Control behaviour changes in heating and ventilation may have remained the same nevertheless the mixed interaction with controls in the post-refurbishment also involves changes in some of their routinised practice which is now determined by the technology and installation deficiencies other than the building fabric condition. The level of

occupants' energy efficiency awareness has also slightly improved despite their poor opinion on the measures due to the lack of information on the low-carbon interventions.

These interrelated factors that were found to directly or indirectly affect occupant interaction with low-carbon measures and the correlations between variables as illustrated in Appendix 37. They need however to be interpreted with caution as they are the findings of an empirical study using a small sample size of social housing. Therefore, the present results provide and need to be considered as an indication of correlations for future research in social housing building stock and low income household energy programmes.

Chapter 9: Discussion and conclusions

In this final chapter the intent of this research and the main findings that emerged are summarised and discussed in relation to the main research question and objectives set in by study. The contribution of the study's outcomes to the knowledge is discussed under the lens of the current literature. The chapter finishes by discussing the study's limitations and the potential opportunities for further research in this area and providing key messages and recommendations from the study's insights for different sectors in building's energy use field.

9.1 Intent of the study

The interdisciplinary approach adopted in this thesis explored user interactions as the central phenomenon in 26 social housing low-carbon refurbishments of a demonstration competition programme the Retrofit for the Future (RfF). The overall aim was to examine the type of interactions between occupants (social tenants) and building systems (innovative low-carbon heating and ventilation systems). The notion of 'interaction' was used by the study to define control-oriented actions between occupants' routinised behaviours and the new elements in the refurbished environment that determine a building's overall in-use performance. The study employed an interdisciplinary approach to analyse complex interrelated technical and non-technical factors involved in occupants' interaction affecting in-use building performance. Engineering, social science and socio-technical theoretical approaches (discussed in Chapter 4) were combined. Different methods and techniques were also integrated to analyse the central phenomenon of interaction within three key areas: technical aspects (physical components of the building system), non-technical (household system of occupants/users) and interaction of both (energy use and operation). The four theoretical approaches used in this study (user-centred theory, interactive adaptivity, practice theory and STS theory) draw attention to

and help interpret particular events of interaction on occupants' routinised practices. The methodological approaches used (thematic, classification, correlation and regression analysis as well as triangulation methods to cross-check occupants' 'doings' and 'sayings')- and tools from buildings' science studies (BPE and POE) have captured and evaluated the distance between a building system's in-use performance and the design intended performance.

The two research questions and objectives central to the study's aim are reviewed and discussed in this section in relation to the achievements and research findings. The first research question looked at what interactions are between low-carbon refurbishment interventions and occupants' behaviour. The objective set was to identify the type (direct/indirect, passive/active) and frequency of occupants' interaction with technical refurbishment interventions.

In a large number of cases in the sample occupants' interaction with both space and water heating involved only repetition of previous heating practices, whereas in the majority of cases combinations of previous and new practices were adopted. Direct heating controls designed and installed for passive users (e.g. controls on the gas boiler) in most of the cases are used 'as designed' and only in a few cases involved active users interacting with the system, which was mainly to overcome technical problems (e.g. to reboot the system). Indirect interaction with conventional and intelligent heating controls has generally fostered occupants' interaction at different levels (good, mixed and full interaction) when no design and installation constraints were involved. However, the findings from occupants' interaction with controls like programmers, intelligent controllers and TRVs show that interaction is not 'as designed' (Figure 126).

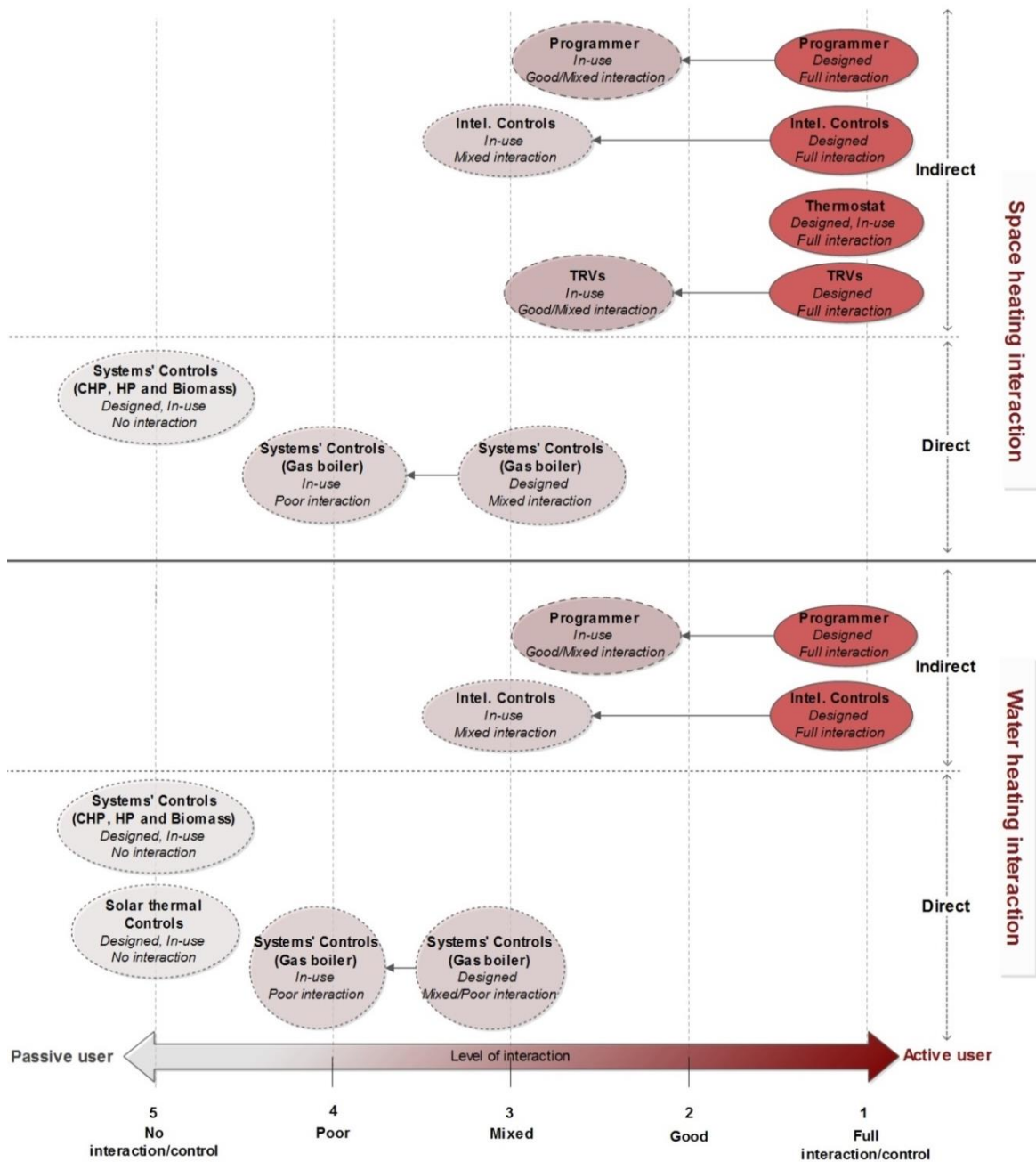


Figure 126: Heating systems and occupants' interaction as designed and in use.

When occupants' adaptive behaviour is not 'scripted'/prefigured by a heating measure the frequency of interaction was found to be comfort and season dependent. Occupants' new interaction experience with the intelligent controllers was found to be mixed as they mostly tried to implement instantaneous control repeating previous heating practices they were used to in conventional heating systems.

From an energy perspective in ventilation although openings (windows and doors) were designed for active users, the majority of occupants' direct interaction is mixed, involving both good and poor operation of the measures. Although active users tend to repeat previous practices for indoor air quality, window operation in post-refurbishment involves number of opened windows and for less time. The frequency of openings' control varies, dependent mainly on the activity that is taking place in the room (cleaning, sleeping, bathing and cooking), and less on the MVHR system requirements for best practice performance. The indirect ventilation measures like windows' trickle vents installed for active users have not involved any interaction, whereas doors' undercut gaps are used 'as designed' for passive users (Figure 127).

In mechanical ventilation systems, interaction with the MEV, although designed for active users, was prevented in almost all the cases by installation faults of the controls. Poor or mixed interaction with MVHR controls was found even in cases when controls were provided. In most of the cases the frequency of interaction with mechanical ventilation systems' controls followed practices of cooking and bathing, whereas other interactions like with air valves to regulate the intensity of the blown air were less frequent.

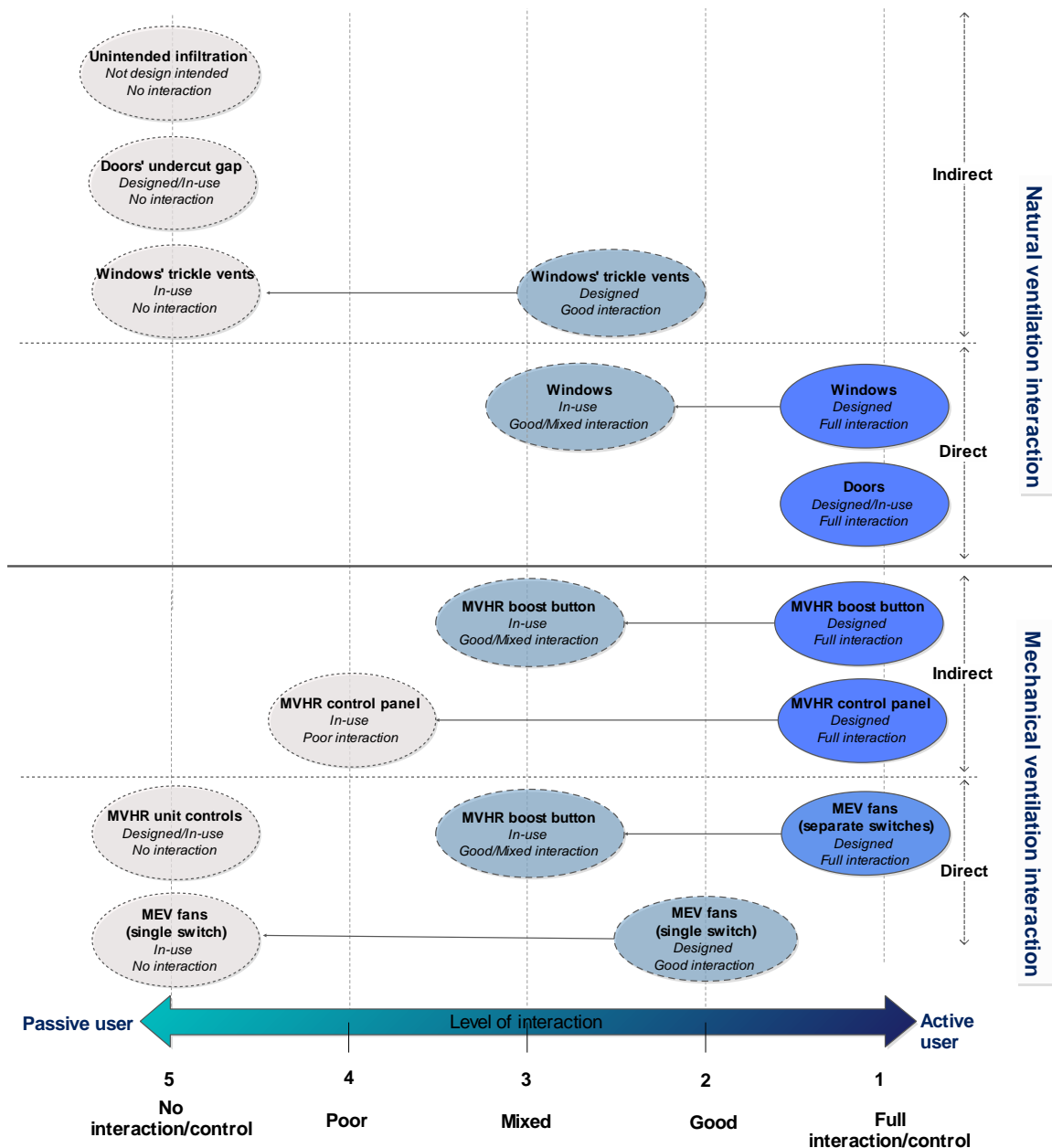


Figure 127: Ventilation systems and occupants' interaction as designed and in use

Generally, the findings indicate that occupants' interaction with heating and ventilation controls follows repetition of previous practices, especially when measures are similar to occupants' past-experience control practices. Occupants' mixed interaction with the low-carbon technology and insights into less adaptive behaviour regarding the new systems controls are the result of several interrelated factors explained by the next research question and objective of this study.

In the second objective of this study is the *cause* and the *effect* of these interactions were examined and the interrelations between socio-technical factors that determine interaction were analysed responding to the research question of *why* and *how* these interactions occur (Figure 128, based on Chapter 1.3, Figure 3 and p.42). Interrelated technical and non-technical determinants were found to cause mixed or poor interactions with heating and ventilation controls. The main socio-technical determinants affecting interaction that emerged from the second research question are illustrated in Figure 128 below.

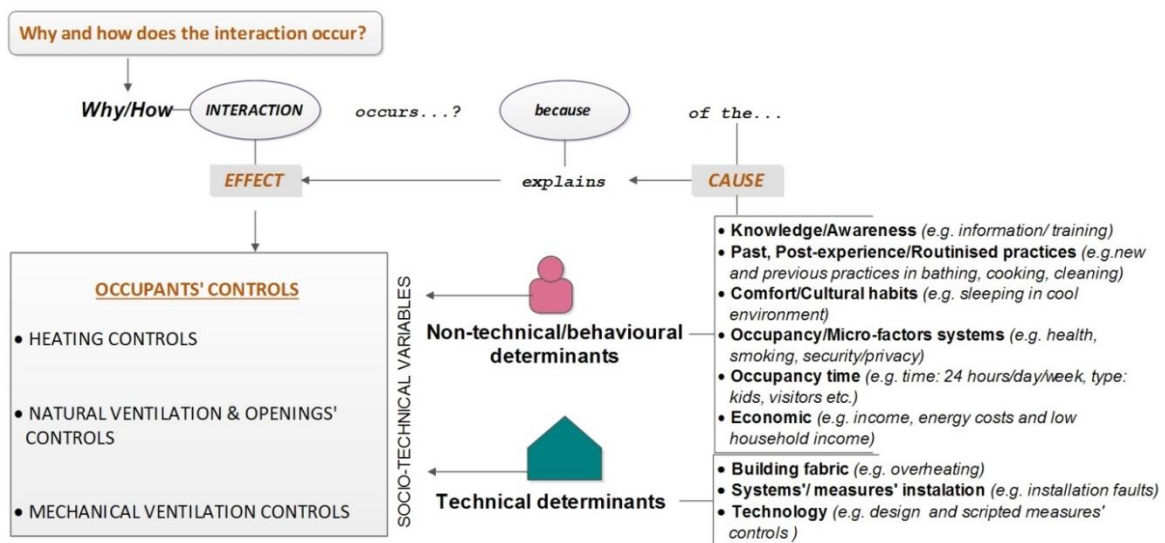


Figure 128: Socio-technical determinants and variables that emerged from the study's second research question.

9.1.1 Technical determinants

Technical determinants of installation and design faults strongly interrelated with physiological and behavioural variables were found to constrain interaction. One of the main causes of poor interaction with heating controls was the lack of communication between the low-carbon heating systems and intelligent heating controls, due to installation problems, resulting in malfunctioning of both space heating and hot water. Similarly in ventilation one of the common problems with the MVHR was the system blowing cold air during the cold months and freezing cold in warm months, due to installation faults, leading to unusual interactions like closing or taping the air valve.

Despite the MVHR booster fan controls in the wet rooms, in some cases the system was found insufficient to extract all the steam and humidity from the bathing and cooking practices. Installation faults of the ventilation and heating systems had a high impact on occupants' controls over the systems (mixed behaviour), which often resulted in electricity use increasing and systems' underperformance their specification standards for comfort and air quality. In the properties with monitoring systems installed to provide energy use feedback to the users different operational problems have again restricted any type of occupants' interaction.

The design and the technology of the products in several cases prescribed occupants' interaction with heating and ventilation controls (both natural and mechanical ventilation). The prefigured options of the Wattbox controller itself, the incapability of the system to respond to users' instantaneous settings in their comfort preferences and occupancy variations, together with the lack of information provided were major problems in occupants' interaction with the new heating systems. Occupants' adaptive behaviour with TRVs was found to be only comfort and season dependent when interaction was not prefigured by the measure.

The design decision of the specific systems installed in some cases has not considered how occupants' lifestyle will co-evolve and interact with the measures in the new building environment (e.g. biomass and manual feeding or Wattbox and occupancy variables). Design issues in ventilation with MEV extractor systems, like one joined (or separate) switcher with the light in the wet rooms or placed in a non-reachable location, constrained interaction, causing occupants to again repeat previous practices of opening windows to achieve indoor air quality. House location (e.g. rural or urban area) and occupants' routinised practices of opening windows were not always considered in the design in relation to the MVHR system. In natural ventilation the most common design issue that

emerged was the window operation problem due to the location of the opening (e.g. above the kitchen counter-top) and the increased width of the wall to achieve insulation standards. The size, the type of the windows and doors installed, and the opening direction have also not considered all design aspects affecting operation in natural ventilation practices and the way activities were co-evolving in the rooms. The improved building fabric allowed occupants' adaptive behaviour to involve new practices like opening windows and doors; in the poor pre-refurbished buildings such actions were not supported due to the constantly cool indoor environment. Other design choices of the building fabric to achieve airtightness standards (e.g. triple glazing) together with the malfunctioning of the MVHR system and occupants' mixed interaction with windows and ventilation system during warm months, were often found to cause rooms' overheating and occupants' interaction that were neither 'as designed' nor 'as modelled'.

In this respect the study agrees with Bunn's views (as cited in Chisholm, 2014:2) highlighting that the success of a project "is judged on operational outcomes as opposed to design specification". In this study the gap between estimated and actual electricity consumption, with the predicted consumption being lower than the actual values, indicates failure of the modelling tools (SAP) to accurately estimate post-refurbishment building performance. A significant drop of the gas consumption in the post-refurbishment stage in cases with gas as a heating fuel (of 42% to 90% of decrease) compared to pre-refurbishment indicates clearly the significant improvement of the building fabric and systems' efficiency. In the cases with CHP the interaction constraints with intelligent controls due to technology (disallow for instantaneous changes in temperature) and installation faults (communication between controller and boiler) had as also as a result the actual consumption fell even below the SAP forecasted levels.

In contrast, decreases in electrical consumption in the post-refurbished house were found in almost half of the cases (varying from 11% to 91%), when compared to the pre-refurbishment. However, there is no evidence to demonstrate to what extent electricity decrease was result of the photovoltaic system installed or of occupants' behaviour changes, as no information or data on electricity generation was given either to the occupants or was available in the TSB database⁵⁸. This study's empirical findings further support the Gill et al. (2010) claim that user behaviour can no longer be considered as the only complex factor for explaining performance deficits, or the only variable that justifies the gap between modelled/estimated and actual performance. The failure of the systems to perform to their standards due to installation faults (e.g. MVHR and ASHP heating), the extra number of occupants living temporarily in the property after works, and occupants' "rebound" behaviour change are some of the factors that may have contribute to electricity increase.

In agreement with previous research (Liu et al., 2012a, Yun et al., 2009) weather variations were found to be strongly related to technical and non-technical determinants, having a significant impact on comfort adaptation and interaction with heating and ventilation controls.

9.1.2 Non-technical determinants

In non-technical determinants strong relationships were found between the three types of knowledge and interaction with controls. Past-experience know-how and occupants' tacit knowledge have been the reasons for repeating previous practices in both conventional and innovative heating and mechanical ventilation systems' controls as well as in natural ventilation routinised practices. The post-experience knowledge was found to be strongly

⁵⁸ The energy metering data provided of electricity and gas in the RfF sample was in kWh allowing the calculation of energy consumption for each property but not the energy demand.

affected by the type, timing and person providing the information/training, as well as by the occupant's individual interest and engagement in gaining knowledge on the low-carbon technology installed.

The conditions for success in interacting and understanding new measures controls 'as designed' were when occupants' personal proactivity and interest in learning about the new measures was combined with a good rapport with the project team and technicians. Especially when occupants lived in the property during works such conditions have proved to offer them not only better level of information on the measures installed but also training that involved several demonstrations on controls during and after works completion.

Contrary to RfF competition expectations, this study found to a large extent a significant absence of in-depth planned information involving visual demonstration of the installed low-carbon measures and combined systems as a whole. Instructions have not always been communicated in a simple, understandable way to the occupants and the lack of visual demonstration of the measures proved to be a serious weakness. In the majority of the cases occupants were found to have lack of information and understanding on what actions and routinized practices are affecting systems performance. The timing of the information provided was a significant aspect, showing that instructions and demonstrations of measures' controls that are neither too early (the day occupants moved into the property) nor too late (several months after) can be effective in becoming occupants' post-experience knowledge. The level of expertise or knowledge the person providing the information ('housing officer') had on each measure and combined low-carbon systems in the RfF properties also proved to be an important factor. For instance, occupants' mixed understanding of how to operate windows and the MVHR system in warmer and cooler months was to some extent related to the mixed information/training they had on the new

measure. One of the key problems in the mixed understanding and interaction with controls has also been the plurality of information and guidance occupants had from different people involved in the project that were lacking of skills and knowledge on the specific measures. As emerged from the sample, it was the lack of not only a well-planned handover and training process, but also feedback on their energy use, that crucially limited occupants' knowledge. Frequent feedback would have helped occupants not only to understand the impact of their interaction with the new combined systems and controls but also to be alerted of the effect their routinised practices have on energy.

Occupants' past and post-experience related to their knowledge has been a significant determinant of how previous and new routinised practices were combined and co-evolved with low-carbon interventions and new technologies in the RfF properties. It is interesting to note that occupants' awareness of their actions affecting building's heating performance (e.g. opening windows when heating is ON) is higher than awareness of affecting the MVHR system in their routinised practices. Therefore, despite the mechanical ventilation systems installed (MVHR or MEV), routinised practices of airing when cleaning, bathing or cooking; cultural habits of opening windows and doors when sleeping or smoking; and occupants' personal values of energy efficiency have been the main causes of occupants' interaction in windows' opening. No interaction or poor occupant interaction with MVHR controls was found even in cases when control is provided and full operation is not scripted by the measure (e.g. filter type, control panel options).

A correlated factor with occupancy in social housing is health, which is also related to occupants' not working occupation status. In these cases with a long time of annual occupancy, physiological parameters related to comfort result in high temperature in both cold and warm months. Health conditions and occupants' age (e.g. women in menopause) were also found to affect individual comfort preferences, whether on the cool or warm

side. Non-technical determinants were also found to be related to other micro-factors like security and privacy. Therefore, doors' interaction in the post-refurbished stage was mainly affected by the privacy factors rather than heating conservation practices. Household income has been a driver for different types of interaction both pre and post-refurbishment. Occupants' in lower income bands regulated indoor temperatures to meet their thermal comfort preferences mainly for economic reasons, i.e. to achieve energy bills' reductions.

9.2 Summary of findings

The findings that emerged from this research in social housing low-carbon refurbishments can be summarised as follows:

a. Design and installation issues:

- i. The success of a whole building refurbishment approach is strongly dependent not only on the choice of energy efficient design and low-carbon technological solutions but also equally on their implementation and installation.
- ii. The insights show a more critical approach needs also to consider other factors before offering one solution and set of technologies to fit all refurbishment cases. Strategies like Passivhaus standards can be, for instance, the most appropriate for airtight performance specifications, but factors like location, occupants' cultural habits and ventilation practices need to be considered in the design choices in relation to the MVHR system and windows. A critical approach may have taken, for instance to MVHR considering that window opening in urban locations is often constrained by privacy, noise and security factors; whereas the performance of MVHR in rural areas was found to be compromised, performance wise, by occupants' routinised practices of opening windows to ventilate naturally their house.
- iii. Design solutions need to take a more occupant-centred approach that also considers social housing occupants' lifestyle and family needs, integrating these aspects into a 'whole house' refurbishment approach and low-carbon design choices (e.g.

MVHR system and smoking habits, biomass and manual feeding, lack of storage space and low-carbon equipment). Long term tenancies in social housing could allow social house providers to involve more participation of the households at the design stage and allow designers to develop a design brief with more user-centred choices.

- iv. Installation problems in several combined systems were found to affect comfort and occupants' interaction with them, whether these were between low-carbon technologies and conventional systems (e.g. gas boiler and solar thermal system) or in communication between low-carbon systems and intelligent controls (e.g. CHP and Wattbox controller).
- v. An important finding was that occupants are active in consciously regulating heating controls repeating previous practices when operation is not prefigured by the measure; or coming up with their own alternatives solutions to adaptive technologies design limitations. This clearly implies that some heating practices are robust against major changes in the building and heating system context with obvious implication for the design of such controls. Occupants' interaction with intelligent controls like Wattbox designed to automatically detect and learn occupants' comfort preferences from their routine repetition has provided insights into the mainstream user control experience with a technology that its main goal is to provide maximum efficiency, comfort and ease-of-use by 'ensuring' that the user only "uses the energy when and where they need it" (AlertMe, 2011). The study argues that heating control technologies as such need to still offer the option of user interaction and control when this is desired being more adaptive to occupants' immediate needs. This echoes previous studies conclusions that adaptive intelligent technologies design may offer advanced functionalities but yet still needs to leave a window for user 'manageability' and operation (Yang and Newman, 2013).
- vi. In natural ventilation, design faults constrain windows' operation due to the increased wall thickness and sill height. Issues related to the usage of the measures need be addressed early in the design process considering different types of windows, handles and opening side location.

- vii. It may have been possible to avoid problem with user controls, system and design faults, if the building system as a whole had been tested thoroughly by the project team before and after works completion, and better support given to occupants when occupied.

b. Knowledge, skills and communication:

- i. Lack of skills and building expertise (e.g. building teams and installers and other people involved in the project) on the specific low-carbon measures and combined systems (e.g. a system of the CHP boiler and solar thermal measures controlled by Wattbox) has been one of the main failures to achieve systems' best practice performance. Occupants' mixed understanding and confusion of the new measures installed was often the result of the many different opinions on system controls from different people involved with the project.
- ii. Lack of knowledge of the specific measures by the project teams and the people involved from the Housing Associations and Councils ('housing officer') suggests not only that there is scope for skills improvement, but also that there is a role for one key person - 'housing officer' - in engaging and communicating information to the occupants, to act as project lead or liaison with the experts, providing demonstration and training to support existing occupants on the specific measures installed and to train future occupants.
- iii. Technical specification manuals, booklets, leaflets and different written material proved to be too technical and not always easy to use. The information needs to be communicated in a simple way, not only via oral information about the refurbishment's interventions and systems installed (whether are conventional or intelligent), but also through a visual demonstration of the controls. The use of different formats like images and audio-visual material that communicates information in occupants' languages could contribute more effectively to users' understanding.
- iv. Information at the pre-refurbishment stage can contribute to a better understanding of the scale of the intervention. This should be focused on introducing to the occupants the specific systems and measures designed for installation in the project.

- v. The instructions/demonstration provided post-refurbishment needs to be well organised and structured, following a measure-by-measure approach within a month after occupants move into the new property (neither too early nor too late), to allow them sufficient time to ‘digest’, interact and familiarise themselves with the new systems and measures.
- vi. Despite occupants’ expectations and consent to live with the energy monitoring equipment, there was generally a lack of feedback on their energy consumption and interaction with the new measures. Monitoring systems installed, like Microwatt energy display, never worked to provide occupants’ with feedback, and feedback on their electricity generation from the photovoltaic was never provided.

c. Types of occupants’ interaction:

- i. Occupants are active users having mixed interaction with intelligent heating controls to regulate their comfort (whether this is to warm up or cool down the indoor environment), mainly by repeating previous practices they were used to with conventional controls. There was good or full interaction with heating controls when these were not ‘scripted’/prefigured (e.g. with default settings) and there were no installation constraints on the combined heating systems and controls. Occupants are generally passive, having poor or no interaction with heating controls which were designed either for passive users (e.g. Wattbox) or for partial interaction with the user (e.g. not user-friendly controls on the heating boiler that often require technical skills).
- ii. Occupants are active users having good or mixed interaction with windows when operation is not scripted by the design or installation faults. In natural ventilation there is less repetition, in both time and frequency, of previous practices in occupants’ interaction with windows in post-refurbishment.
- iii. Poor or mixed interaction with mechanical ventilation (MEV and MVHR) controls is the result of design or installation faults, involving also repetition of previous practices (e.g. opening windows, turning on electric fans) that follow occupants’ routinised activities and affect measures’ performance.

- iv. Frequency of interaction with heating controls is comfort and season dependent, whereas with ventilation controls it varies in addition in accordance with the activity taking place in the room (e.g. cleaning, bathing, cooking etc.).

d. Interactive adaptivity:

- i. Overall indoor air quality in the RfF properties has considerably improved compared to previous conditions in all cases in the sample, with occupants being generally satisfied with post-refurbishment comfort levels. The improved building conditions affected occupants' adaptive behaviour for comfort often resulting from rebound interactions.
- ii. Occupancy time, occupants' health conditions and occupational status in social housing are correlated and affect indoor comfort conditions, which often appears as internal temperature increase. Comfort adaptation to lower temperatures was found in lower income bands in the sample.

e. Other insights from the RfF sample:

- i. Training and malfunctioning of the measures have considerably affected occupants' opinions about the low-carbon measures installed, as they had no insight into a system working properly to its specifications.
- ii. Occupants' knowledge transfers from previous heating comfort practices and controls and post-refurbishment installation failures have been largely compromised and overwhelmed by 'forgiveness' and 'forget' factors of living in a better environment on the whole.

9.3 Study's contribution to knowledge

The discussion in this section is structured with reference to the summary of findings and the thesis's objective presented in 9.1 and 9.2 and relates them back to the deficiencies identified from the literature review. The aim and objectives set out in previous sections were achieved by following an interdisciplinary cross-project investigation into the in-use performance of deep 'whole house' refurbishments. The primary output offers new insights into user's control behaviour with low-carbon measures in heating and ventilation.

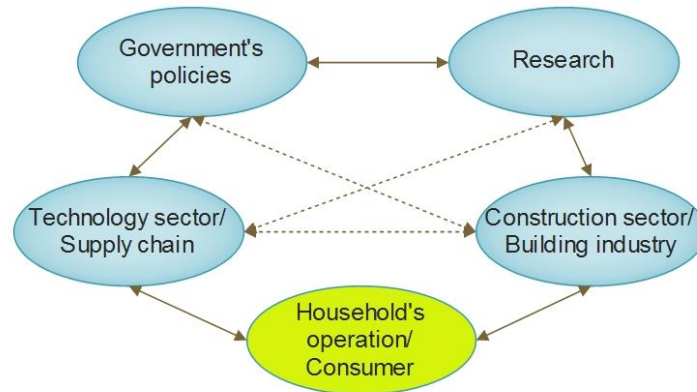


Figure 129: The main areas of contribution from the study's outcomes (based on Figure 1, p.38).

The main contributions of this research fall into four distinct areas (Research, policies, technology and building industry) all affecting directly or indirectly a household's operation and energy consumption:

- i. In the current context of domestic energy use this research is a pioneering academic cross-project investigation into the performance of deep 'whole house' refurbishments using an inter-disciplinary approach. Findings are helpful for any country or programme on deep refurbishment filling a gap in the literature on existing empirical research in low-carbon housing refurbishments, especially in the social housing sector which has not been explored yet in detail. The household has previously mainly been analysed from engineering or socio-economic perspectives (e.g. Radian, 2010, Fawcett et al., 2013) but not as a 'whole-house' system of complex interrelated technical and non-technical components that are equally involved in low-carbon energy use performance. In this respect the primary contribution of the present thesis comes from the analysis of the occupants' interaction with low-carbon domestic technologies, providing insights into the in-use stage to all sectors (researchers, policy makers, building and technology industry). The majority of the findings indicate the problems affecting refurbishment interventions and complex systems' components in installation and performance efficiency, confirming the broadly accepted gap between the actual and predicted performance.

- ii. The interdisciplinary approach of this thesis also contributes in research in terms of methodology bridging separate technical and social approaches that consider energy use from either one or the other perspective. This study improves upon technical approaches that assume ‘average’ or ‘default’ users, by showing how active or passive user interactions relate to different technical measures. It also improves upon conceptual approaches and theoretical frameworks that view energy from solely behavioural and socio-economic perspectives, by providing details of how technical determinants affect users’ routinised practices. The methodological and theoretical synergies and links in the study have overcome previous studies’ limitations in applying merely one theory or method to investigate the complex interrelated socio-technical issues in energy use.
- iii. This thesis has also provided an original contribution to the Retrofit for the Future competition of Technology Strategy Board, which was at the time, the largest retrofit programme and the only significant monitored demonstration of deep refurbishment in the UK. The research has provided additional and complementary data to the RfF by employing further collection techniques and methods focusing on the interactions of the occupants with building systems. This input also allows a novel assessment to be made of the combination of techniques and approaches that future deep refurbishment programmes need to consider for strengthening the quantity and quality of data. Issues found to be affecting data quality and quantity in the RfF monitoring process that emerged from this study can be considered as feedback on the monitoring process for future similar schemes. The in-depth analysis and findings of the present thesis also contribute to the RfF project’s analysis, complementing studies that focus solely on economic aspects of social house refurbishments, on technical perspectives (e.g. building fabric), or on social aspects (e.g. occupants’ rapport with the project team and relocation issues affecting retrofitting process), but not on aspects of occupants’ interaction with the specific innovative low-carbon measures (Institute for Sustainability, 2012b, Institute for Sustainability, 2012a, TSB, 2013, Sweett, 2014).
- iv. Understanding the constraints in occupants’ interaction with the refurbished home can contribute towards a more effective approach to design choices, installation processes and occupants’ training in future studies of domestic energy use. The insights from the design and installation faults in the sample can be a guide on

specific areas that need to be addressed in the initial refurbishment design stage, on installation and before and after a project's delivery (e.g. Darby, 2008, BSRIA, 2014) . There are several studies dealing with how occupants' knowledge and technical intervention information need to be delivered. However, this thesis can contribute to the still limited evidence on the impact and effectiveness of instructions and training techniques when they are on complex low-carbon systems and controls (e.g. CHP, solar thermal and Wattbox or domestic MVHR systems and natural ventilation).

Due to the small sample of social housing households (n=26), this thesis can offer initial indicators that can be tested and evaluated in larger samples to inform policymakers and contribute to the policy design stage, as well as to practitioners, housing associations and local authorities in relation to higher levels in refurbishment implementation and the support stage in the coming years.

9.4 Study's limitations

The factors that have constrained the study's research have been discussed throughout this thesis. This section discusses some of the aspects that were not explored as well as certain limitations of this thesis that draw potential opportunities for further research discussed in next section.

When the RfF project ran in 2009-2010, this was, for the construction sector, a particularly difficult period as a result of the general economic crisis. Increased redundancy in the construction sector and liquidation of building companies and supply chain actors at that time in the UK were factors that affected the RfF refurbishment process. In most cases the difficulties reported were mainly with the project management and related to the key person responsible on-site for providing handover and useful information about the project and the measures, as well as maintenance and technical support during and after works. In many cases the key person changed several times along with contractors and sub-

contractors. This has made things more difficult as the person or the installation teams that took over did not always have the knowledge or training on the innovative technology and measures installed in the RfF properties. This had implications on the information and guidance occupants had on controls and usage, on the installation of low-carbon system and measures, and on the support and maintenance occupants can have now after the completion of the RfF competition. Taking the above into consideration, the time that the RfF project took place may have limited how technical and non-technical factors co-evolved in the refurbishment process. However, for some cases in the sample this is not the only reason for failing to achieve competition targets and the ‘as designed’ performance. Issues like these, although they might be common in project site management, indicate the need for further research.

A constraint for this research was the monitoring data provided by the TSB. The physical data inputs available in the online database (Embed⁵⁹) were not of the same quantity and quality for all cases. This was mainly due to the fact that the requirements of the physical monitoring process were broadly specified by the competition, leaving project teams with choice in managing the monitoring data and equipment. This resulted in unequal levels of detail in meter readings (gas and electricity consumption) and physical data (internal temperatures, CO₂, relative humidity) that varied from all rooms to just some rooms. As discussed in Chapter 6, the main issues raised with the data were: long data intervals (e.g. missing weeks or months); odd values (e.g. Lounge B CO₂ 4.2197 ppm); monitoring equipment that followed different units and data formats (e.g. electric pulse, kWh and kW); different coding for the monitored rooms (e.g. main bedroom and front bedroom or lounge B and dining room); and variation in the choice of meter readings and in the rooms to be monitored (e.g. data for PV electrical output pulse but not for electricity

⁵⁹ The physical data and documentation of the RfF project provided by the Technology Strategy Board is at the ‘embed’ online database (source: https://est.amee.com/user_session/new).

consumption); as well as the lack of meaningful window opening-closing data as its fundamental to any occupant interaction in housing. The competition agreement and cost issues involved have deterred this study from conducting the focus group discussions as intended and proposed to the TSB. Many of these limitations suggest the importance of a more rigorous framework and detailed specification protocols for data collection with the type and quality being uniform. Given that in all cases households complied with the RfF competition agreement, respecting the importance of the monitoring equipment and project team's requirements for frequent access high quality data was obtained only when project teams have undertaken a detailed monitoring process. In this respect one of the key areas that needs further study, is the strategy to achieve cost effective monitoring solutions that secure high levels of data quality and quantity in which different stakeholders can comply.

9.5 Opportunities for further research

Overcoming data limitations can offer the opportunity for further research on occupants' interaction. The availability of more detailed data meter readings (especially in terms of quality) of households' energy consumption can allow investigation of the extent to which such interactions affect the actual consumption in the refurbished homes. This could allow identification of the level of importance (low/zero, medium, high) that socio-technical variables have on social housing energy consumption and define the extent to which interacting factors affect energy use.

With regard to future research another issue that emerged from the RfF sample was the carbon embedded in transport and manufacture of the low-carbon system and measures (e.g. triple glazed windows imported from Germany), assembly, installation and technical support (e.g. installation teams or Wattbox technicians more than 100 miles away). Although part of the RfF programme involved interviews with the supply chain (e.g. project teams, builders and contractors) there is still very little data publically available

that allows further detailed research on the embodied energy of the specific low-carbon measures/systems installed and services provided in the RfF whole-house refurbishments sample.

One of the issues explored in this research was how low-carbon refurbishment interventions were initially designed and actually implemented. The insights from this study could feed into the overall evaluation of retrofit processes, shaping indicators for more efficient delivery and better outcomes of similar schemes in the future. However, further research following empirical ‘whole house’ approaches is needed, exploring other factors that may bias the ‘as designed’ and ‘as constructed/installed’ stage in mass refurbishment programmes.

Finally, there is the importance of such demonstration schemes and of their achievements being used as ‘hero stories’ (Janda B.K. and Topouzi, 2013), although we need to be very cautious of the exact message they convey. However, what is equally important for learning from these challenging refurbishment programmes for all sectors and disciplines are the ‘horror stories’ highlights, of those factors which have resulted in behaviour not being ‘as designed’. This research may have contributed to practical knowledge by identifying some of the in-use stage factors that can perhaps transformed from a ‘horror story’ to a ‘learning story’, if communicated in constructive ways to different sectors. However, the repetition of the same or similar mistakes or omissions in buildings refurbishment clearly indicate that the ‘learning from our mistakes’ approach has not been entirely successful and perhaps the ways to communicate such issues are not sufficiently clear and effective. The point about the learning stories it is about interaction and cannot be considered as ‘horror stories’ but need to be treated with the same priority as the ‘hero stories’ to have an effective impact. The study suggests that more exploration of the communication tools and learning process strategies from the ‘learning stories’ is required.

This needs to be designed for diverse needs, using different means for each sector (practitioners, commerce, householders and academics) and go a step further than generating (or re-generating) knowledge mainly for academic and research use.



Figure 130: The gap between design stage and construction -implementation/installation-, (source: <http://bere.co.uk/blog/scaling-retrofit-%E2%80%93-need-opportunities-and-difficulties>).

The loss of knowledge between the design to construction (implementation/installation) stage and the lack of communication between (and within) the different sectors involved and users are particularly important to be addressed if buildings' energy performance gap is to be reduced and future policies are to set out realistic targets to achieve.

9.6 Key messages for different sectors

An outline of recommendations on the main key issues emerged from this study for the different sectors are summarized as follows:

a. Recommendations for policy makers

- i. The barrier to short and long terms policy visions, action programmes, regulations and standards involving energy efficiency improvements in vulnerable low income households and hard-to-treat properties in social housing, still remains critical at the level of interpretation, implementation and at the degree of effectiveness. The targeted energy reduction policies in these groups can be more effective given that

economic related energy cost factors and improved building environments are found to be strong motivators for occupants' behavioural change; and energy awareness increase especially when feedback processes are involved. Mass low-carbon intervention programmes would need to incentivise different stages of aftercare support at the post-construction stage. This would include monitoring reviews and feedback processes to and from the users, from the initial occupancy period and up to the first two years of the building in-use, using POE and BPE processes. The use of this reciprocal feedback approach *to* and *from* the user ('learning story') is substantial first for the users to understand the effect that their practices and interaction with the building system have on energy use (e.g. in RfF case how much electricity is generated by the solar technology installed in their property and which routinised practices need to change to benefit the most). And also important for the policy makers to evaluate the degree of effectiveness and implementation of such low-carbon schemes from evidence based feedback of the in-use performance (e.g. provide modelling inputs from evidence based insights of the solar technology at in-use stage).

- ii. Technical problems and installation faults that emerged from the design to construction stages in low-carbon buildings are found to significantly affect a building's in-use performance and occupants' interaction with the new low-carbon interventions. Incentivise mandatory quality controls at post-refurbishment stage like the BSRIA (2014) Soft Landings (SL) guidance approach, in which quality controls and 'reality-checks' before the building handover and occupants' actual use is suggested. Making mandatory diagnostic building evaluation and tests at the pre-refurbishment stage technical issues related to the building system and non-technical aspects of the household system could be integrated early at the design

stage. This can allow select low-carbon intervention design choices that fit better to the users.

- iii. Publically available evidence based data is currently very limited and often varies in terms of quantity and more importantly of quality and time. This renders difficult to support policy initiatives evaluations or modelling approaches as evidence based data does not always captures both qualitatively and quantitatively, and for long periods, building's energy use. To overcome current data related problems data quality protocols and detailed data collection standards for both qualitative and quantitative data (e.g. provide specifications on sensors location, units and coding templates for measurements etc.) need to be established and should also be made mandatory. The requirement to increase long term data collection entails incentivising the development of new cost effective monitoring and metering tools. Technology Strategy Board and Research Councils or other trusts need also to boost similar initiatives like the Low energy building database ('embed') to provide publically available both qualitative and quantitative data in row and aggregated formats. When collection follows the same protocol and standards quantity, quality and dissemination of data could significantly expand the reservoir of evidence base from low-carbon case studies. This would increase building refurbishment knowledge in different sectors reducing the gap between estimated and in-use performance.
- iv. In 'whole-house' deep refurbishments complex of low-carbon systems and combinations of measures were often found to underperform due to installation failures as a result of multi skills deficiency in the current building professions. Meeting the low-carbon skills challenge requires incentives not only for improving the building expertise on single technological innovations but to create new

structures of multi skill professions with knowledge to support combined systems and ‘whole house’ intervention approaches. Incentivise an innovation curve in which the current rigid boundaries of traditional professions would not just move towards single skills expertise but to combined low-carbon services that could support current challenging best practice performance standards.

- v. The loss of knowledge between the design, construction (implementation/installation) and in-use stages, the lack of communication between (and within) the different sectors and the ways knowledge is disseminated to a building’s users, have also a significant impact to buildings’ energy performance gap problem. Incentivise other communication channels like creating an evidence base ‘Bank of Failures’ and ‘Successes’ from different low-carbon refurbishment trials in the UK. In this, ‘horror’ and ‘hero stories’ would need to be treated the same to have an effective impact making low-carbon buildings’ learning curve progress. ‘Horror’ stories (Janda B.K. and Topouzi, 2013) are often drowning in the loss of knowledge holding back approaches like ‘learning from our mistakes’. A ‘bank’ as such could provide to different sectors (policy makers, research supply/ building industry and building users) valuable learning lessons from past-experiences avoiding repetition of the same failures.

b. Recommendations for housing providers

- i. Occupants’ relocation during deep refurbishment interventions in social housing is a major issue for social housing providers. In the RfF competition the two different approaches in refurbishment management of room-by-room and whole building intervention has shown that the former approach increased project duration and resulted to mutual disruption for both occupants and project management. Room-by-room deep refurbishments may be a choice in private tenures as different level

of engagement with the deep refurbishment work process is involved. In social housing however occupants' relocation options need to be prioritised in the project management to reduce refurbishment works costs, time and disruption.

- ii. Deficiencies on the handover and lack of aftercare support of refurbished low-carbon buildings of existing approaches found to result major problems in buildings operation, maintenance and energy use performance for both users/occupants and social housing providers. Considering that long tenancies are a big account in social housing efficient training is fundamental as it puts the roots on occupants 'new' tacit knowledge of innovative technology structuring their practices to reduce consumption. Occupants' handover and training/demonstration several times after occupancy from a high skilled person on the installed measures needs to be ensured. There are different stages that handover information and training could take place: Stage 1, early pre-handover (pre-refurbishment) introduction of the building system and design solutions proposed. This stage would ensure that occupants/users' life style and family needs comply with the proposed low-carbon interventions. Keeping simple visual material or leaflets with basic technical information proposed measures are introduced; Stage 2: Handover (on-site) in the first few weeks of occupancy providing measure-by-measure visual demonstration. Occupants would be left with audio-visual material with systems/controls' demonstration of their own house or with simple visual manual that explains step by step combined systems/controls operation (repetition of Stage 2 demonstration process after 6 months); Stage 3- aftercare service and maintenance involves on-site for checking systems and measures mal-operation following with informal chat with the occupants to identify interactions that may affect performance (repetition of Stage 3 operation check and feedback reviews

every year preferably during heating season). A contact list for technical support for each measure or combined systems would also be provided and updated every year during Stage 3 visit. The key person ('housing officer') assigned for the specific houses need to be well trained on the specific measures installed with visual demonstrations from expertise on the measures operation after 'reality-checks' and before the occupants' handover.

c. Recommendations for the supply chain and building industry

- i. Current building design standards and high low-carbon specification are becoming a priority for the design teams. Design solutions may tick all boxes of standards combining measures and systems with high performance modelling assumptions; however factors affecting building underperformance and user satisfaction lay on basic architectural design and installation principles often placed in second order. New challenges on design may have incorporated high level dynamic modelling tools and technological innovation in building refurbishment; however design team choices require more critical approaches on the design stage keeping in balance technical specifications and user-centre solutions.
- ii. High performance standards in deep refurbishments include complex combined systems and controls that require particularly high specifications on the construction stage. However, installation failures found to decrease best practice performance and increase operational complexities of occupants' interactions with building system at the in-use stage. Design solutions need to be kept simple and well communicated by the design team to project team (project manager, contractors, technicians, installers etc.) which needs to provide the credentials to adequate knowledge on the combined low-carbon systems and controls proposed.

Project manager would need to have a key role from the design development to the final pre-handover ‘reality checks’ stage. This role requires comprehensive experience on the specific measures installed (trained by expertise or technicians) and flexibility to provide on-site design solutions avoiding installation failures (e.g. MEV systems controls placed in non-reachable height). A robust project planning and management in such complex refurbishments would also ensure a project’s stability securing best practices performance in construction beyond markets’ turbulences.

- iii. As discussed above low-carbon combined systems require multi skills and expertise on combined low-carbon technologies. Certification of skills on new technologies often is undermined by online courses on individual systems lacking of ‘whole-house’ approach and combine systems practical experience. In building industry low-carbon multi skills/knowledge on combined systems needs to be supported by practice-based training on actual low-carbon deep refurbishment trials like the Retrofit for the Future competition was in the UK. This would allow creating low-carbon training hubs in which theoretical design aspirations and combined cutting edge technologies can be explored into practice based experience skill training.

Finally to these recommendations a fitting conclusion to the main argument of this thesis is that to decrease the distance between estimated and actual energy use the notion of ‘interaction’ is and always needs to be seen as a reciprocal process between the ways building system components are designed/installed and occupants’ control-oriented actions of routinised behaviours co-evolve to create indoor comfort.

Appendices

Appendix 1 The Standard Assessment Procedure (SAP) is the methodology used by the Government to assess and compare the energy and environmental performance of dwellings in order to comply with the UK's energy and environmental policy initiatives (e.g. Buildings Regulations for England and Wales and the Devolved Administrations, Energy Performance Certificates, Code for sustainable homes, Warm Front, Green Deal, Energy Company Obligation etc.). Developed by the Building Research Establishment (BRE) was cited as a tool in Part L of the Building Regulations for assessing dwelling performance. The performance indicators are based on estimates of annual energy consumption for the provision of space heating, domestic hot water, lighting and ventilation that quantify performance in terms of: energy use per unit floor area, a fuel-cost-based energy efficiency rating (the SAP Rating 1 to 100 efficiency) and emissions of CO₂ (the Environmental Impact Rating). Other SAP outputs also include estimate of appliance energy use, the potential for overheating in summer and the resultant cooling load as well as fuel costs and emissions of carbon dioxide (CO₂), can also be determined from the assessment. The assessment uses standardised assumptions for occupancy and user behaviour to enable a like-for-like comparison of dwelling performance (<https://www.gov.uk/standard-assessment-procedure>, 2014).

Appendix 2 BRE Domestic Energy Model (BREDEM 2012) is the methodology for the calculation of the energy use and domestic fuel requirements based on buildings' characteristics. Although it shares similar features with SAP methodology this assessment tool is suitable for research modelling housing stock and for certain analysis as it allows more flexibility in inputs that are fixed in SAP. BREDEM considers not only building characteristics but also some aspect of the occupants' lifestyle like occupancy patterns and bathing routines for space heating and hot water respectively.

Appendix 3 Non-decent homes by tenure from 2006 to 2012 and criteria of failing decent homes standards(Source: DCLG (2014b).

Table 13: Homes failing decent homes criteria, by tenure, 2012

<i>all dwellings</i>					
	minimum standard (HHSRS)	thermal comfort	disrepair	modern facilities	all non-decent
<i>thousands of dwellings</i>					
owner occupied	2,027	906	623	177	3,002
private rented	779	627	324	112	1,365
private sector	2,806	1,533	947	289	4,366
local authority	134.67	61	81	51	289
housing association	98	145	51	36	292
social sector	233	206	132	87	581
all dwellings	3,039	1,739	1,079	376	4,947
<i>percentages</i>					
owner occupied	13.7	6.1	4.2	1.2	20.3
private rented	18.9	15.2	7.9	2.7	33.1
private sector	14.8	8.1	5.0	1.5	23.1
local authority	7.6	3.4	4.6	2.9	16.3
housing association	4.8	7.1	2.5	1.8	14.3
social sector	6.1	5.4	3.5	2.3	15.2
all dwellings	13.4	7.7	4.8	1.7	21.8

Notes:

1) the 'minimum standard' is calculated using SAP09 methodology, and is based on 15 HHSRS hazards to maintain consistency with previous years' decent homes reporting

2) figures in *italics* are based on small samples and should be treated with caution

Source: English Housing Survey, dwelling sample

Table 12: Non-decent homes, by tenure, 2006 to 2012

<i>all dwellings</i>							
	2006	2007	2008	2009	2010	2011	2012
<i>thousands of dwellings</i>							
owner occupied	5,335	5,304	4,842	4,377	3,784	3,292	3,002
private rented	1,223	1,244	1,449	1,465	1,381	1,407	1,365
all private	6,558	6,548	6,291	5,842	5,165	4,698	4,366
local authority	676	652	625	491	391	334	289
housing association	465	486	444	389	369	332	292
all social	1,142	1,138	1,069	880	760	666	581
all dwellings	7,700	7,686	7,360	6,722	5,925	5,364	4,947
<i>percentages</i>							
owner occupied	34.6	34.1	32.3	29.3	25.5	22.3	20.3
private rented	46.8	45.4	44.0	40.8	37.3	35.0	33.1
all private	36.3	35.8	34.4	31.5	27.8	25.0	23.1
local authority	32.4	32.8	31.5	27.1	21.7	17.7	16.3
housing association	25.2	25.5	22.8	19.7	18.3	15.9	14.3
all social	29.0	29.2	27.2	23.2	19.9	16.6	15.2
all dwellings	35.0	34.6	33.1	30.1	26.5	23.6	21.8

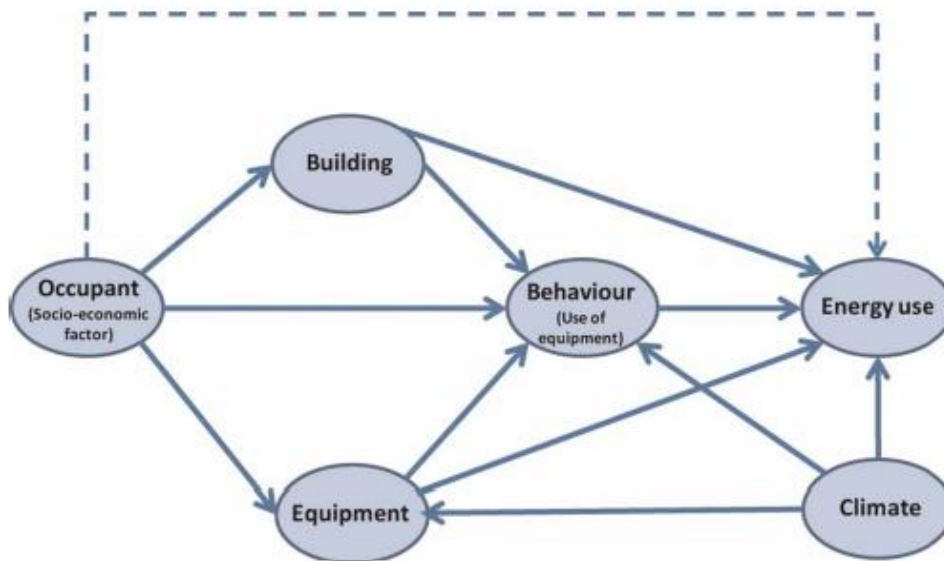
Note: 2006 to 2009 estimates based on SAP05 methodology; SAP09 methodology applied from 2010. The change in methodology does not make a significant difference to the estimates of non-decent homes. See the glossary and the 2011-12 Headline Report for more information

Sources:

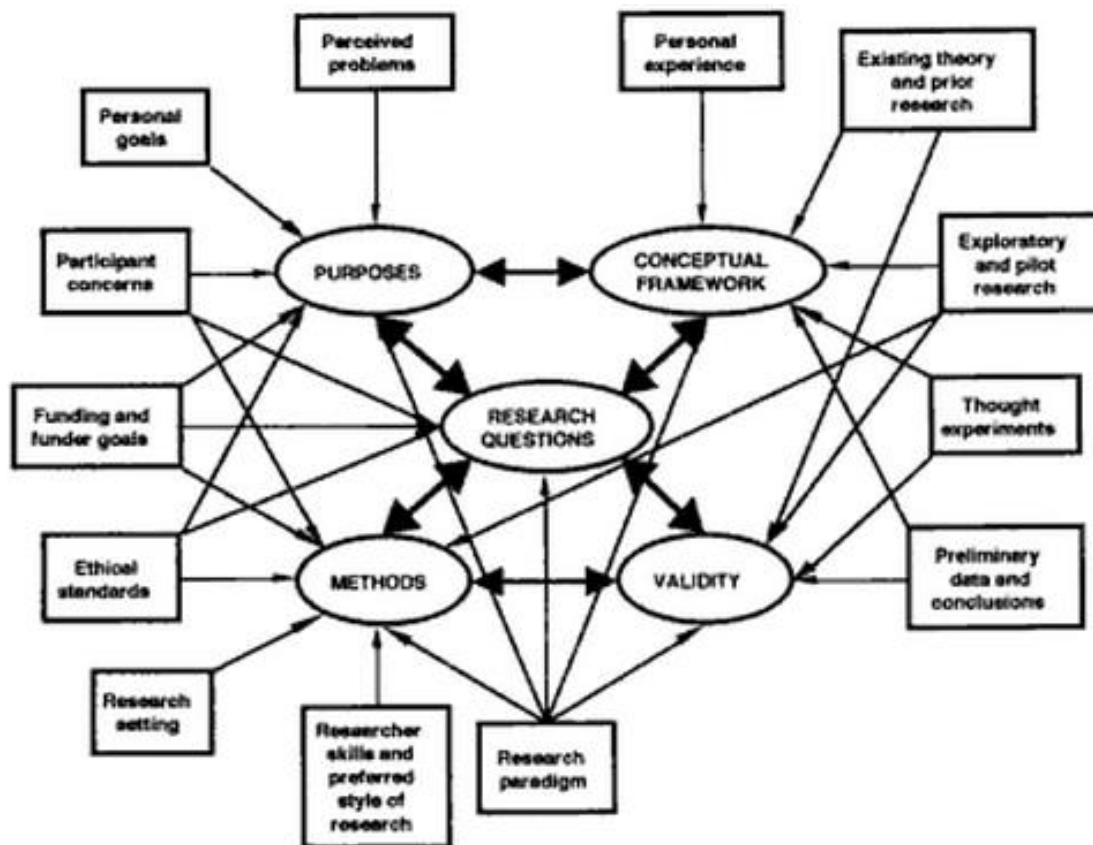
2006 to 2007: English Housing Condition Survey

2008 onwards: English Housing Survey, dwelling sample

Appendix 4 Steemers and Yun (2009), diagrammatic representation of factors effecting domestic energy use adapted to the study's conceptual framework.



Appendix 5 Maxwell and Loomis (2003), Interactive design approach: Contextual factors influencing a research design.



Level of interaction with the measure	Occupant (s)
(1) Full interaction/ control	Complete level of control (usage); occupant(s) understands completely how to operate the technology; and he is fully aware of how his (their) behaviour could affect measure performance
(2) Good	Good level of control (usage); occupant(s) good understanding of how to operate the technology and he is partly aware of how his (their) behaviour could affect measure performance
(3) Mixed	Some level of control (usage); occupant(s) mixed understanding of how to operate the technology but he (they) are confused with how his (their) behaviour could affect measure performance
(4) Poor	Low level of control (usage); occupant(s) poor understanding of how to operate the technology but he (they) are very confused with how his (their) behaviour could affect measure performance
(5) No interaction/ control	Little /none level of control (usage), very poor understanding where occupant(s) did not know how to work the measures at all; and occupant(s) did at all understand how their behaviour might affect measure performance

Appendix 7 Table 21: Factor and variable classifications established from previous research.

Factors/ Variables			Classification			Research Study
Type	Direct (Dir.)	Indirect (Ind.)	Influence [aspects]	Determinants/ Dependencies	Correlation/ Impact [in energy use]	Author
Non-technical (Social)	Economic	Income	(Dir.) Number of heated rooms, type of house, age of house, size of house, number of windows, type of equipment/(Ind.) Heating consumption, temperature Type of house (bought or rented) Size of house	<i>Physical aspects: (climate, heating type, age of house, and size of house) –most significant determinants of household heating energy</i>	Strong Strong Strong	Steemers and Yun (2009) Carlsson-Kanyama and Linden (2007), Steemers and Yun (2009) Aune, Berker et al (2002)
		Education	Size of house		N/A	Aune, Berker et al (2002)
		Age of the householder	(Dir.) Size of house/ (Ind.) Type of equipment, number of heated rooms, heating energy consumption (Dir.) Cooling		Not taken into account for the regression model Not taken into account	Steemers and Yun (2009)
	Demographic	Family size	(Dir.) Size of the house, number of windows, number of heated rooms/ (Ind.) Heating consumption (Dir.) Cooling Energy use		Not taken into account for the regression model Not taken into account Big influence	Steemers and Yun (2009) Steemers and Yun (2009) Schipper L. Bartlett S., et al. (1989)
		Composition	Energy use		Big influence	Schipper L. Bartlett S., et al. (1989)

Physical infrastructure	Occupancy factors		Hours of occupancy	Energy use		Big influence	Schipper L. Bartlett S., et al. (1989)	
	Occupant (interaction)			Space heating DHW Cooking, lighting, and cooling miscellaneous appliances	<i>End-use:</i> very dependent on occupant interaction <i>End-use:</i> very dependent on occupant interaction <i>End-use:</i> less dependent on user interaction	Most important Most important N/A	Schipper L. Bartlett S., et al. (1989) Schipper L. Bartlett S., et al. (1989) Schipper L. Bartlett S., et al. (1989)	
	Climate		Weather	Weather	Type of equipment, heating consumption Number of heated rooms, average room temperature		Strong Strong	Steemers and Yun (2009) Steemers and Yun (2009)
	Technical		Type of the house	Type of the house	Building type (Dir.) Number of heated rooms/ (Ind.) Type of equipment, heating consumption		Small influence Strong	Schipper L. Bartlett S., et al. (1989) Steemers and Yun (2009)
			Age of the house		(Dir.) Number of heated rooms			
			Size of the house		Dwelling size (Dir.) Type of equipment, number of heated rooms, heating consumption		Big influence Strong	Schipper L. Bartlett S., et al. (1989) Steemers and Yun (2009)
			Number of windows		(Dir.) Number of heated rooms, heating consumption		Strong	Schipper L. Bartlett S., et al. (1989)
			Type of equipment		(Dir.) Number of heated rooms, heating consumption (Ventilation and heating) Systems prefigure habits related to comfort.		Strong Big influence	Steemers and Yun (2009)
			House layout		House prefigures its use		Big influence	

Appendix 8 Study's thematic analysis and impact of variables in energy use, variables coding and types of data sources.

KEY AREAS, THEMES, VARIABLES AND DATA SOURCES						Primary sources					Secondary sources							
KEY AREAS	THEMES	CAUSE			EFFECT (Interaction/Energy use)		Essential Information phone survey	Observations walk by (external)	Observations walkthrough (internal)	Semi-structured interview	In-situ meterings	Google map	EST/TSB RETROFIT FOR THE FUTURE Case studies Documentation	EST/TSB RETROFIT FOR THE FUTURE Database monitoring meterings	Degree Day Data	PHPP Modelling	SAP Modelling	
		Sub-theme	Question ID	VARIABLE CAUSE	Direct/ Indirect/ Linked													
Technical components: Building system	Building context	Climate:	(C1)	Building Orientation	Direct	Building and systems performance		Textual data				Textual data cross check						
			(C2)	External temperatures	Direct	Building and systems performance					Numerical data				Numerical data	Numerical data	Numerical data	
		Building:	(B1)	Building Status (Conservation restrictions)	Linked	Building intervention performance/ design solutions/ comfort	Textual data cross check	Textual/ Visual data cross check						Textual data				
			(B2)	Age	Direct	Performance/ Type of equipment (systems)/	Textual data cross check	Textual/ Visual data cross check						Textual data			Numerical data	Numerical data
			(B3)	Type	Direct	Performance/ number of heated rooms/(ind. Comfort)	Textual data cross check	Textual/ Visual data cross check						Textual data			Numerical data	Numerical data
			(B4)	Tot. floor area	Direct	Performance/ number of heated rooms/(ind. Comfort)								Textual data			Numerical data	Numerical data
			(B5)	Storeys	Direct	Performance/ number of heated rooms/(ind. Comfort)		Textual/ Visual data cross check	Textual/ Visual data cross check					Textual data			Numerical data	Numerical data
			(B6)	Number of rooms	Direct	Performance/ number of heated rooms/(ind. Comfort)			Textual/ Visual data cross check					Textual data				
			(B7)	Space layout	Direct	Performance/ number of heated rooms/(ind. Comfort)			Textual/ Visual data cross check									
		(B8)	Extensions/porches/conservatories	Direct	Performance/(ind. Comfort)		Textual/ Visual data cross check	Textual/ Visual data cross check					Textual data					
	Building fabric	Physical components:	(BF1)	External walls	Direct	Building and systems performance/(ind. Comfort)		Textual/ Visual data cross check	Textual/ Visual data cross check				Textual and numerical data			Numerical data	Numerical data	
			(BF2)	Ext. Walls finish	Direct	Building and systems performance		Textual/ Visual data cross check	Textual/ Visual data cross check				Textual data					
			(BF3)	Partition walls	Direct	Building and systems performance/(ind. Comfort noise)			Textual/ Visual data cross check				Textual data					
			(BF4)	Roof /Loft	Direct	Building and systems performance/(ind. Comfort storage space)		Textual/ Visual data cross check	Textual/ Visual data cross check				Textual and numerical data					
			(BF5)	Floors	Direct	Building and systems performance/(ind. Comfort)			Textual/ Visual data cross check				Textual data				Numerical data	Numerical data
			(BF8)	External shading Devices	Direct	Building and systems performance/(ind. Comfort light)		Textual/ Visual data cross check					Textual data				Numerical data	Numerical data
			(BF6)	Windows	Direct	Building and systems performance/ comfort/heating , ventilation controls		Textual/ Visual data cross check	Textual/ Visual data cross check				Textual and numerical data				Numerical data	Numerical data
	Building system	Type of equipment:	(HS1)	Heating system	Direct	Building and systems performance/ comfort	Textual data cross check		Textual/ Visual data cross check				Textual data			Numerical data	Numerical data	
			(HS2)	Heating space type	Direct	Building and systems performance/ comfort/controls	Textual data cross check		Textual/ Visual data cross check				Textual data				Numerical data	Numerical data
			(HS3)	Heating Hot water type	Direct	Building and systems performance/ comfort/controls	Textual data cross check		Textual/ Visual data cross check				Textual data				Numerical data	Numerical data
			(M1)	Condensing Boiler	Direct	Building and systems performance/ comfort/controls	Textual data cross check		Textual/ Visual data cross check				Textual data				Numerical data	Numerical data
			(M2)	Solar panels	Direct	Building and systems performance/ comfort/controls	Textual data cross check	Textual data cross check	Textual/ Visual data cross check				Textual data				Numerical data	Numerical data
			(M3)	MVHR/ Fans	Direct	Building and systems performance/ comfort/controls	Textual data cross check		Textual/ Visual data cross check				Textual data				Numerical data	Numerical data
			(M4)	Solar PV	Direct	Building and systems performance/ comfort/controls	Textual data cross check	Textual data cross check	Textual/ Visual data cross check				Textual data				Numerical data	Numerical data
			(M5)	Sun pipe light	Direct	Building and systems performance/ comfort/controls	Textual data cross check		Textual/ Visual data cross check				Textual data					
			(M6)	Intelligent control systems	Direct	Building and systems performance/ comfort/controls	Textual data cross check		Textual/ Visual data				Textual data					
			(BS2)	Combined Systems and Integrated low-carbon solutions	Direct	Building and systems performance/ comfort/controls			Textual/ Visual data cross check				Textual data				Numerical data	Numerical data
		Building-system intervention:	(BS1)	Level of intervention	Direct	Building and systems performance/ comfort			Textual/ Visual data cross check				Textual data				Numerical data	Numerical data

KEY AREAS, THEMES, VARIABLES AND DATA SOURCES					Primary sources					Secondary sources								
KEY AREAS	THEMES	CAUSE			EFFECT (Interaction/Energy use)		Essential Information phone survey	Observations walk by (external)	Observations walkthrough (internal)	Semi-structured interview	In-situ meterings	Google map	EST /TSB RETROFIT FOR THE FUTURE Case studies Documentation	EST /TSB RETROFIT FOR THE FUTURE Database monitoring meterings	Degree Day Data	PHPP Modelling	SAP Modelling	
		Sub-theme	Question ID	VARIABLE CAUSE	Direct/ Indirect/ Linked													
Non-technical components: Occupant/user	Demographic	Demographic:	(D1)	Occup.Num.	Direct	Occupancy / Controls/ Comfort	Textual data			Textual data cross check						Numerical data	Numerical data	
			(D2)	Gender	Indirect	Occupancy / Controls/ Comfort	Textual data			Textual data cross check								
			(D3)	Age group	Direct/Indirect	(Dir.)Size of thehouse/ (Ind.)Occupancy / Controls/ Comfort/ heating consumption	Textual data			Textual data cross check								
			(D4)	Family composition	Direct/Indirect	Occupancy / Controls (roles in control)/ Comfort/ number of heated rooms	Textual data			Textual data cross check			Textual data					
			(D5)	Cultural background	Direct	Behavioural comfort (use/ control)/ embodied habits				Textual data								
			(D6)	Health conditions	Direct	Physiological comfort (use/controls/ occupancy)				Textual data								
			(D7)	Smoking	Direct	Lifestyle/ habits/ Controls/ Comfort					Textual data cross check	Textual data						
			(D8)	Pets	Indirect	Behavioural comfort (use/ control), Occupancy patterns					Textual data cross check	Textual data						
		Economic	Economic:	(E1)	Education/ Qualifications	Indirect	Knowledge/ Perceptions/ Values/ Lifestyle				Textual data							
			(E2)	Occupation	Direct	Occupancy patterns, financial					Textual data							
			(E3)	Income	Direct	Behavioural comfort (use/ control)					Textual data							
		Occupancy patterns	Occupancy:	(OP1)	Occupancy background (tenants before and after)	Indirect	Experience/ behaviour change	Textual data			Textual data cross check		Textual data					
			(OP2)	Relocated during works	Indirect	Experience, Satisfaction with the process/ involvement with design process	Textual data			Textual data cross check								
			(OP3)	Living period in RfF property	Direct	Experience / level of awareness/ behaviour change	Textual data			Textual data cross check			Textual data					
			(OP4)	Average occupancy in typical Week (Mon-Fri)	Direct	Comfort/ controls/ Interaction				Textual data				Numerical data				
			(OP5)	Average occupancy per Weekends (Sut-Sun)	Direct	Comfort/ controls/ Interaction				Textual data				Numerical data				
			(OP6)	Average occupancy annually	Direct	Comfort/ controls/ Interaction				Textual data				Numerical data				

KEY AREAS, THEMES, VARIABLES AND DATA SOURCES						Primary sources					Secondary sources								
KEY AREAS	THEMES	CAUSE			EFFECT (Interaction/Energy use)		Essential Information phone survey	Observations walk by (external)	Observations walkthrough (internal)	Semi-structured interview	In-situ meterings	Google map	EST/TSB RETROFIT FOR THE FUTURE Case studies Documentation	EST/TSB RETROFIT FOR THE FUTURE Database monitoring meterings	Degree Day Data	PHPP Modelling	SAP Modelling		
		Sub-theme	Question ID	VARIABLE CAUSE	Direct/ Indirect/ Linked														
Socio-technical components: Interaction	Energy Behaviour	Perceptions/ Values/ Lifestyle:	(CUE1)	Opinion of the property prior to installations	Indirect	Past-experience /Awareness/ Views/ Expectations				Textual data									
			(PE1)	Bills payment	Direct	Income /Behaviour change/ comfort/ controls				Textual data									
			(BC1)	Level of Green lifestyle, energy saving changes	Direct	Awareness/ perceptions/ behaviour change				Textual data									
		Past/Post Experience:	(CE1)	Change in energy bills	Direct	Income/ Behaviour change/ Awareness, Views, Expectations				Textual data									
			(BC5)	Pre-installation level of occupant EE behaviour	Indirect	Awareness/ Views/ Expectations				Textual data									
			(BC6)	Post-installation level of occupant EE behaviour	Indirect	Awareness/ Views/ Expectations				Textual data									
		Engagement:	(SE1)	Support for the process	Linked	Personal Values/ Awareness/ perceptions				Textual data									
			(DP1)	Tenants participation in design	Indirect	Comfort/ controls/ Awareness				Textual data									
			(BC4)	Behaviour change due to monitoring	Linked	Controls/ Interaction/ Awareness				Textual data									
			(TS1)	Instructions/training (Type)	Direct	Awareness/ Knowledge/ Comfort/ controls				Textual data									
	(ME2)		Training provided (measure)	Direct	Awareness/ Knowledge/ Comfort/ controls				Textual data										
	Awareness/Views/ Expectations	Perceptions/ Values/ Lifestyle:	(BC2)	Awareness of energy of electricity and gas use in the house	Direct	Awareness/ perceptions/ behaviour change				Textual data				Numerical data	Numerical data	Numerical data	Numerical data		
			(BC3)	Other level of awareness regarding the retrofitting process	Direct	Awareness/ perceptions/ behaviour change				Textual data									
		Past/Post Experience:	(ME1)	Opinion of the measure	Indirect	Controls/ Interaction				Textual data									
			(CUE3)	Understanding of previous heating controls	Direct	Engagement/ knowledge/ control/ behaviour change				Textual data									
		Comfort controls:	(ME5)	Understanding Actions affecting measure performance	Direct	Awareness/ perceptions/ knowledge/ control			Textual/ Visual data cross check	Textual data									
	Satisfaction	Past/Post Experience:	(SE2)	Satisfaction with the process	Indirect	Comfort/ Awareness/ perceptions/ Values , lifestyle				Textual data									
			(IPS1)	Improvements designed, as build	Indirect	Comfort/ Awareness/ perceptions/ Values , lifestyle			Textual data cross check	Textual data									
			(IPS2)	Process (duration/ disruption/ cleanliness)	Indirect	Comfort/ Awareness/ perceptions/ Values , lifestyle				Textual data									
		Values:	(IPS3)	Level of satisfaction of the property prior to installation	Linked	Overall Comfort (property)/ Awareness/ perceptions/ Values , lifestyle				Textual data									
			(IPS3)	Level of satisfaction of the property post installation	Linked	Overall Comfort (property)/ Awareness/ perceptions/ Values , lifestyle													
	Engagement:	(TS2)	Level of instruction Satisfaction level	Indirect	Awareness (Knowledge)/ perceptions/ Values/ Qualification				Textual data										
	Comfort and controls	Building comfort:	(IES1)	Property condition	Direct	Satisfaction/ Comfort/ controls			Textual/ Visual data cross check	Textual data									
			(IES2)	Health effects from property conditions	Direct	Comfort/ controls			Textual data cross check	Textual data									
			(CUE2)	Comfort level of the property prior to installation	Direct	Past-experience/ thermal comfort				Textual data									
			(IES3)	Draughts	Direct	Past/Post-experienceComfort/ controls			Textual data cross check	Textual data									
			(IES4)	Damp/ mould/ internal air quality	Direct	Past/Post-experienceComfort/ controls			Textual/ Visual data cross check	Textual data									
			(IES5)	Smell	Direct	Past/Post-experienceComfort/ controls			Textual data cross check	Textual data									
			(IES6)	Natural Light	Direct	Past/Post-experienceComfort/ controls			Textual data cross check	Textual data									
			(IES7)	Noise	Direct	Past/Post-experienceComfort/ controls			Textual data cross check	Textual data									
			(IES8)	Security	Direct	Past/Post-experienceComfort/ controls			Textual data cross check	Textual data									
			(DS1)	Overall design	Direct	Past/Post-experienceComfort/ controls			Textual/ Visual data cross check	Textual data									
		Comfort controls:	(DS2)	Change room sizes	Indirect	Past/Post-experienceComfort/ controls			Textual data cross check	Textual data									
			(OC4)	Number of heated rooms	Direct	Occupants' Controls/ use													
			(OC1)	Overall comfort (Temperature)	Direct	Energy behaviour Physiological adaptation/ controls				Textual data	Numerical data				Numerical data	Numerical data			
			(OC2)	Overall comfort (To cool down)	Direct	Behavioural adaptation/heating-ventilation controls				Textual data	Numerical data				Numerical data				
			(OC3)	Overall comfort (To warm up)	Direct	Behavioural adaptation/heating-ventilation controls				Textual data									
			(CU1)	Passive Ventilation Windows Control and use (Summer)	Direct	Occupants ventilation Controls/ equipment use			Textual/ Visual data cross check	Textual data									
			(CU2)	Passive Ventilation Windows Control and use (Winter)	Direct	Occupants' heating-ventilationControls/ equipment use			Textual/ Visual data cross check	Textual data	Numerical data				Numerical data				
(CU3)			Passive Ventilation Doors Control and use	Direct	Occupants' heating-ventilation Controls/ equipment use			Textual/ Visual data cross check	Textual data										
(CU4)			Heating space Control and use	Direct	Control/comfort/ habits /window operation, active-passive heating systems, health condition/ occupancy patterns, active-passive users,			Textual/ Visual data cross check	Textual data	Numerical data				Numerical data					
(CU5)			Nat. Lighting controls Control and use	Indirect	Controls/ use (indirect to heating)			Textual/ Visual data cross check	Textual data										
(CU6)	Active Ventilation Control and use	Direct	Controls/ use/ habits, comfort, expectations/ active-passive system, active-passive users,			Textual/ Visual data cross check	Textual data	Numerical data				Numerical data							
(CU7)	Heating Hot water Control and use	Direct	Controls/ use/ habits, comfort, expectations/ active-passive system, active-passive users,																
(ME4)	Level of control (usage) measure	Direct	Controls/ equipment use use/ behaviour change			Textual/ Visual data cross check	Textual data												

BUILDING SURVEY CHECKLIST

Interview info	
Database Code:	[25]TSB102 (Chr. Alder project manager) Peabody -
Interviewers:	Marina (Oxford)
Lead occupant (Interview):	Male-Female (mainly)
Date of visit:	08/02/2012
Time of visit:	16:00pm
Type of interview:	vs.1_Occupant before the works
Occupancy	couple - daughter 34 and 29 (young daughter). -33 years - * 3 smokers - open windows and doors. Living room
Interview room:	
Address:	6 Elizabeth Place, Clyde Road Terrace, London, N15 4LA
(L1) Area/ Site position characteristics	social housing complex - residential area park with playground on the side - - female parttime / daughter Full time - 2 weeks max. - male retired all day home - she works with disable children
Climate	
(C1) Orientation	North West front façade (check) (rear garden south facaded)
(C2) External temperature	10C cloudy -
Building	Observation list As Build
(L2) Ext. Building environ.	small space (2 cars parked)
Disabled access	No step to the property
Building Status	4 houses rehurbols -
Age/ Type	End terrace, 1970s,
Tot. floor Area (m2)	97 m ²
Number of Storeys	2
Number of Rooms	3 bedroom
Extensions/porches/conservatories	→ extension to the communal border -
Building Fabric	
External walls	brick cavity walls/ External wall insulation - Permarock 200mm
Ext. Walls finish	Plaster
Intern. Walls finish	Plaster
Partition walls	not insulated / nothing on the existing walls has changed. She provided them the paints to paint it interwallly
Roof/Loft	Top up loft insulation
Windows	Triple glazed throughout → bigger windows in throughout house because of fault masonry
Floors	laminat (light wood) in
External doors	New good quality / Livingroom and kitchen / carpet in corrie and 2 bedrooms, study room laminat -
External shading Devices	No - bathroom linoleum (all old ones BC)

* income (level 4)

* except Room MVHR, Ri's and solar thermal no other intervention done to the property.

Heating system	
Heating system	They took out old boiler. There is now 1 domestic boiler for all four properties, which is linked to the solar thermal and MVHR.
Heating space	Communal boiler <i>NVHR was closed the day of the interview out for several months -</i>
Heating Hot water	Solar thermal, again communal
Measures /LZC Technologies	
Solar PV	(rear facade)
Solar thermal	(rear facade)
Boiler	Communal
MVHR	Yes → <i>in summer when working was freezing cold - they had no control</i>
Internal environment	
Overall	Base case (Before works) After Works
(S1) Property condition	windows were easier to operate before.
(CU 2) Health effects from property conditions	→ No only on the rear doors
(S2) Draughts	No
(S3) Damp/ mould/ internal air quality	No
(S4) Smell	No
(S5) Natural Light	No difference with previous
(S6) Noise	→ no noise difference from AC to BC. - No change.
(S7) Security	+ Yes feel security -
Design	
(S8) Overall design/ Space Layout	G/F: living room + dining room, kitchen,
(S9) Change room sizes	- change of the window size (not on purpose by mistake measures of size) -

* no radiators in the house
 * heating-cooking provided by MVHR
 * MVHR system on a cupboard in 1st floor -

* Not good instructions (no manual or training - heating is not working)
 * summer doors open (slightly warmer) -

- Female she doesn't like the outside aesthetics -

- smokers

- Electric Fire place -

* From 6 months (end July) to 16 months final duration of the project - October (finished) - still snagging list.

- No design choice (the only influence they had was on the living room window room -

- 4 project manager - (bad project managing - lack of communication - works were done all over the house) -

Appendix 10 Example of the study's Post Occupancy Evaluation internal observation list.

Retrofit for the Future competition: Interview [Part 2]

08 Feb 2012

WALKTHROUGH						
Room by room: Living Room (and Dining room open room)						
BF(L1) Occupancy: (How much do you or the other occupants use this room? on average every day)	made in all the time -					
BF (L2) Room environ.	Draughts No	Damp/ mould/ int. air quality Not good	Smells smoky	Security Yes	Noise No	Furniture ok (to study)
Comfort	As build		Level of control (usage):			
BF(3) Room comfort: (Please could you indicate on this scale (show comfort card scale) how the room feels normally? What about over...)	Too warm / Warm / Comfortable / Cool / Too cool they prefer it to		Winter: Summer:			
Heating: (What do you do to warm up? Explore use of secondary heaters, turning up the thermostat, turning up the TRV...).						
BF(4) Radiators	Type: Electric Fire Old / New place.					
Ventilation: (What do you do to cool down? Explore use of fans, opening windows, portable air conditioning...)						
BF(5) Natural / Mech. Ventilation	Type: MVHR 2 Fan (one facing to living room and kitchen)					
BF(6a) Windows: (Which windows in this room do you open/ how often?)	Type: 1 big one 2 pivot 1 door window					
BF(6b) Internal doors	Number: 1 door Old / New / Renovated		closed.			
Lighting: (During the day, do you find this room to be bright/ ok / dim.... Do you do anything to control the level of natural light...)						
BF(7) Natural Light:	Satisfaction: very sat					
BF(8) Artificial Light	Satisfaction:		Number:	Type:		
	(dimmer) roof mounted		4 spots - 11 floors and			
BF(9) Internal walls (Is this room insulated Where is this? How has this affected the room...)	Finish: Plaster		Colour:	Hangings:		
BF(10) Floors	Type: Laminated		Colour: light wood.			
OTHER: X no new floors or insulates						

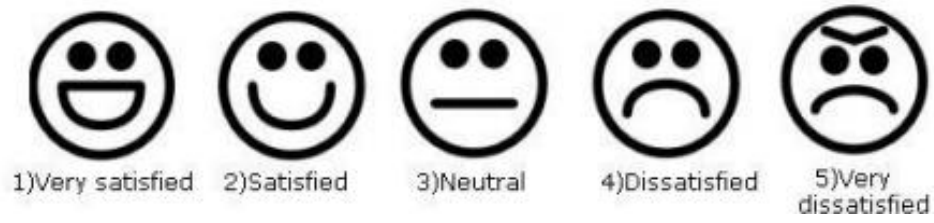
Dining room + living room (open plan).

Interview monitoring Measurements		Room: Living Room		
Measurements	Value	Time 6:00	Value / Time 6:10	Value / Time
BF(1) CO ₂ (ppm)	1594	1104	1170	
BF(2) Int. Temp (°C)	19,9	19,1	20,0	
BF(3) Humidity (%)	67,3	39,4	39,8	

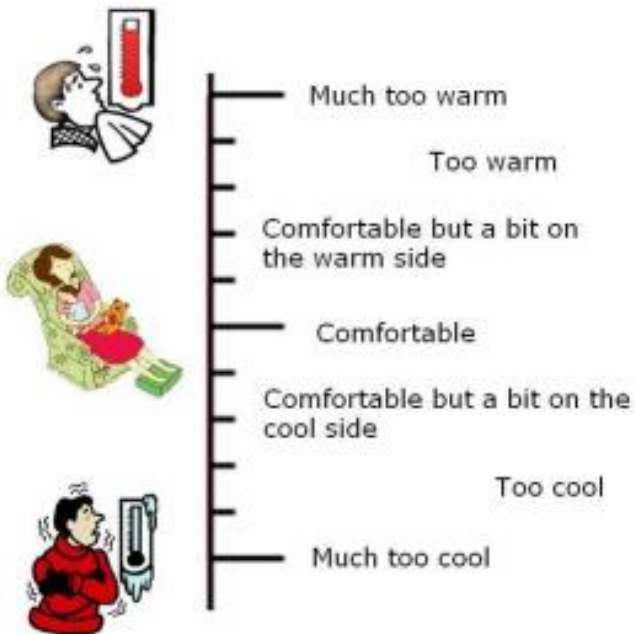
→ Dining room * the time of the interview the electric fire place was ON (to in the living room)

Room by room: Kitchen						
BF (L1) Occupancy: (How much do you or the other occupants use this room? on average every day/ How often do you cook? Is this at the same time as the other occupants? What do you tend to cook? How long does it take? Does this make the room too hot? If so, how do you cool the room?) <i>evening. energy 6-8.</i>						
BF (L2) Room environ.	Draughts	Damp/ mould/ int. air quality	Smells	Security	Noise	Furniture
Comfort	As build		Level of control (usage)			
BF(3) Room comfort: (Please could you indicate on this scale (show comfort card scale) how the room feels normally? What about over...)	Too warm / Warm / Comfortable / Cool / Too cool <i>When cooking</i>		Winter: Summer:			
Heating: (What do you do to warm up? Explore use of secondary heaters, turning up the thermostat, turning up the TRV...).						
BF(4) Radiators	Type: Old / New <i>NO</i>					
Ventilation: (What do you do to cool down? Explore use of fans, opening windows, portable air conditioning...)						
BF(5) Natural / Mech. Ventilation	Type: <i>MVHR</i>		<i>cook extractor (filter hot air)</i>			
BF(6a) Windows: (Which windows in this room do you open/ how often?)	Type: <i>↓ big (pivot + upper tilt)</i>		<i>-always open slightly. (no change w/ previous behaviour)</i>			
BF(6b) Internal doors	Number: <i>Old / New / Renovated</i>					
Lighting: (During the day, do you find this room to be bright/ ok / dim.... Do you do anything to control the level of natural light...)						
BF(7) Natural Light:	Satisfaction: <i>sat.</i>		<i>light curtain</i>			
BF(8) Artificial Light	Satisfaction:		Number:	Type:		
			<i>3 spots (old) roof</i>			
BF(9) Internal walls (Is this room insulated Where is this? How has this affected the room...)	Finish: <i>Plaster tiles</i>		Colour:	Hangings:		
BF(10) Floors	Type:		Colour:			
OTHER:						

Interview monitoring Measurements		Room: Kitchen		
	Measurements	Value / Time	Value / Time	Value / Time
BF(1)	CO ₂ (ppm)	<i>1610</i>	<i>1592</i>	
BF(2)	Int. Temp (°C)	<i>20,0</i>	<i>19,9</i>	
BF(3)	Humidity (%)	<i>42,8</i>	<i>42,8</i>	



Satisfaction scale



Comfort scale

Post Occupancy Evaluation in-depth semi-structure interview topic guide.

- Did the property smell?
- How much natural light did you get in the property? (how bright was it during the day: bright, okay, dim). How much light do you like in the property?
- How noisy was it? (very, slightly, not at all)
- How secure did you feel the property was?

- How warm or cool do you liked the house to be?
- Before the installation work, please could you indicate on this scale (show card scale) how the property felt normally:



- If too warm/much too warm:
 - What did you do to cool down? Explore use of fans, opening windows, portable air conditioning.
- If too cool/much too cool:
 - What did you do to warm up? Explore use of secondary heaters, turning up the thermostat, turning up the TRV.

1.1.1.1 Topic guide for occupants who were tenants before and after the works were undertaken

Timing: Interviewer should allow about 45 minutes for pre tour questions and about 45 minutes for the tour and closing questions.

Introduction (Allow 5 to 10 minutes for this section)

- Introductions and brief chat. Reassurance that there are no wrong answers and how much they know about the work that was done is not important.
- Confirm information provided in the occupant recruitment interview e.g. number and background of the occupants, how long they have been in the property, who works and what they do.
- Reiteration that the interview will be recorded, a walkthrough will be conducted and photos may be taken. Permission for this should be sought.
- Explanation of the confidentiality statement.

Pre-installation experience

- How long have you been living here? Have there been changes in the number of people living here since you moved in?
- (if multiple occupancy) How long have the other occupants been here?

Base Case – Same Property Pre-Installation

- Please could you tell me what the property was like before the building and installation work was started?
 - Was there anything you particularly liked about the property?
 - Was there anything you particularly disliked? Did you have any problems with the property?
 - Did the house have any draughts?
 - Were there any damp / mould / internal air quality problems?

- Did you want the work to be done? Were you offered a choice?
- Did you know that the work was part of a scheme which involved only 115 social housing properties across the UK? How does that make you feel about it?
 - More positive - why?
 - No strong feelings
 - Less positive - why?
- What were your expectations of the whole process? Were you clear on:
 - What was being done to the house and what things were being added to it?
 - The purpose of the work? Were you told what the expected benefits of the work would be?
 - How long the building and installation work would last?
 - How much disruption the works would cause?
 - Whether or not you would be able to live here whilst the works were going on?

QUANTITATIVE CODING:

Support for the process	Very positive / supportive	Positive	Neutral (both positive and negative views)	Neutral (disinterested)	Negative	Very negative / strongly opposed
Quality of explanation of the process	Excellent; occupant seemed fully aware of the entire process	Good	Mixed	Poor	Very poor; occupant(s) did not know what the process entailed	

Satisfaction with the process

- How often did you open the windows?
- How many windows did you open usually?
 - Open all the time - why?
 - Open at least once a day - why? For how long?
 - Rarely open - why not? How often and for how long?
 - Never open - why not?
 - When (day/night)?
- [if mentioned any issue with temperature, humidity, draughts, damp] Do you feel that the conditions in the property prior to the building and installation work affected your health in any way? If so, how?
- What sort of heating controls did you have in the property? Did you find them easy or difficult to use?

QUANTITATIVE CODING:

Opinion of the property prior to installations	Very positive	Generally positive	Neutral	Generally negative	Very negative
Comfort level of the property prior to installation	Excellent	Good	Neutral / tolerable	Poor	Very poor / intolerable
Understanding of previous heating controls		Good	Mixed	Poor	

Introduction to RFF

- How did it come about that your property was selected for the works?
 - When did you find out that this property would be getting building and installation work done?
 - How did you find out? Who told you? Do you remember what exactly you were told at the time?
 - Were you 'picked' for some reason?
 - When you found out, how did you feel about it?

- Bearing in mind the expectations you were given of the process, how closely did the actual process match those expectations?
 - Did it take as long as you were told it would?
 - Yes
 - No → took less time
 - No → too longer
 - Did you get the improvements you were told you would get?
 - Yes
 - No → what was different?
- [IF THE PROCESS DIDN'T GO AS ORIGINALLY PLANNED] Do you know why?
- Did you live in the property whilst the work was being done?
 - Yes
 - No → where did you live? For how long? Did this cause any problems for you?
- [if they stayed in the property during the work] What was it like living in the property whilst the works were going on? Were there any problems during the installation work?
- I am going to ask you about aspects of the work and I would like you to indicate your level of satisfaction with them on this scale (show smiley face 1 to 5 satisfaction scale). The aspects are:
 - How long the work took to complete from start to finish
 - The level of disruption caused by the work
 - The cleanliness of the property after the work had finished



Handover/training for the house as a whole

- Were you given instructions / training on how the improvements are supposed to be used?

- Were you given instructions / training on how you could change your behaviour in the home (with regards to energy use) to maximise the benefits of the technologies?
- [if given any instructions / training]
 - How was this done?
 - Could the instructions/training have been better? If yes, how?
 - Overall, can you indicate on this scale (show smiley face satisfaction scale) how satisfied you were with the level of instruction/ training you were given?
- [if not given any instructions / training]: would you have liked some?
- Since the works were formally finished, has there been any more work that they have needed to do? (second fixes, rectifying problems etc)?
 - Were you expecting this to happen?
 - What did this involve?
 - Did this cause any problems for you?
 - Has this changed the way you feel about the property?

QUANTITATIVE CODING:

Opinion of the installation process	Very positive	Positive	Neutral (both positive and negative views)	Neutral (disinterested)	Negative	Very negative
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Comparison to previous

- Please could you tell me what the property is like now in comparison to before
 - Is there anything you particularly like about the property now?
 - Is there anything you particularly dislike now?
 - Have the pre-work problems with the property that you mentioned earlier been resolved? Are there any new problems since the works?

**[room by room/ measure by measure exploration]
WALKTHROUGH (Allow around 40 minutes for this section)**

Would it be okay for you to take us round your property? It would be great if you could tell us a little bit about each room and perhaps show us all the things that you think were done as part of the building and installation work?

*[Interviewer should have a table of installed measures, including lighting]
[Note – ask respondent to compare to before works, where possible]*

ROOM BY ROOM

- How much do you / the other occupants use this room?
 - i. Every day for a number of hours
 - ii. Every day but only very briefly
 - iii. On average, less than once a day – why?
- Please could you indicate on this scale (show comfort card scale) how the room feels normally? What about over Winter?
- If too warm/much too warm: What do you do to cool down? Explore use of fans, opening windows, portable air conditioning.
- If too cool/much too cool: What do you do to warm up? Explore use of secondary heaters, turning up the thermostat, turning up the TRV.
- Which (if any) windows in this room do you open?
- During the day, do you find this room to be:
 - i. Bright
 - ii. Okay (don't need the lights on)
 - iii. Dim (need lights on)
- Do you do anything to control the level of natural light? (e.g. use blinds or other shading systems)
- [if had EE bulbs] What about at night? Are the bulbs bright enough for what you want to do?

- Does the house now have any draughts?
- Are there any damp / mould / internal air quality problems?
- Does the property smell?
- How much natural light do you now get in the property? (how bright is it during the day: bright, okay, dim).
- How noisy is it? (very, slightly, not at all)
- How secure do you feel the property is?
- [if had internal SWI] Have you noticed that the room is smaller? Has this had any effects on you / placing of furniture etc?

- Please could you indicate on this scale (show temperature card scale as above) how the property now feels normally?
- If too warm/much too warm: What do you do to cool down? Explore use of fans, opening windows, portable air conditioning.
- If too cool/much too cool: What do you do to warm up? Explore use of secondary heaters, turning up the thermostat, turning up the TRV.
- How often do you open the windows?
- How many windows did you open usually?
 - i. Open all the time – why?
 - ii. Open at least once a day – why? For how long?
 - iii. Rarely open – why not? How often and for how long?
 - iv. Never open – why not?
 - v. When (day/night)?
- [If new windows installed] Are they easier/ harder/ no different to use?
- [if mentioned any issue with temperature, humidity, draughts, damp] Do you feel that the conditions in the property affect your health in any way? If so, how?
- What sort of heating controls do you have in the property? Did you find them easy or difficult to use?

- Is there any issue with damp or condensation in this room? Is this all the time or just when you are using hot water etc? How do you cope with this?
- Do you have any other issues with this room? Mouldy / smelly?
- [if had wall insulation] Where is this? How has this affected the room?

(Kitchen only):

- Tell me about cooking:
- How often do you cook? Is this at the same time as the other occupants? What do you tend to cook? How long does it take? Does this make the room too hot? If so, how do you cool the room?

MEASURE BY MEASURE

For all measures (active and passive):

- What is this measure?
- Do you understand what it is supposed to do? What is this?
- Do you think it works? (Yes/No)

For active measures:

- How well can you work this measure?
 - Completely
 - Fairly well but still learning
 - Can work it but not very confident
 - Not at all
- Could you show me how this measure works? (opportunity to record settings)
- Has someone shown you how this measure works?
- Have you been given written instructions on how to use it (are there instructions on it?) If yes:
 - Have you read the instructions?
 - Were they useful?
 - Could the instructions/training have been better? How?
- If not received instructions (training or written):
 - Would you have liked any training/instructions on how the measure works?

- If so, what sort of training/instructions would you have liked?
- Do you think it is doing what it is supposed to do? Could you tell if there was a problem with it?
- Who would you get in touch with if you were having trouble working the measure or thought it might have broken?
- Have you had any problems with the measure so far? If yes:
 - What was the problem?
 - How did you/do you deal with the problem?
 - Do you feel you can resolve/control the problem?
- Do you think this type of technology is:
 - Very common?
 - Fairly common?
 - Fairly unusual?
 - Very unusual?
- Do you like it?
 - If yes, why?
 - If no, why not?
- Do you or anyone else in the house have qualifications from school or college or work or university around engineering or building work? What qualifications of any sort do people in the house have?

ADDITIONAL MEASURE SPECIFIC QUESTIONS

- Condensing Boilers
 - How does this operate?
 - Do you have it switched on all the time or just when you need heating?
 - Can you set to a specific temperature? What temperature is it set to?
- Biomass
 - What fuel do you use in this?
 - How often do you have fuel delivered?
 - Do you know how to load the boiler with the fuel?
- Solar Hot Water
 - Do you use the solar heated water when you bath / shower?

- If you don't mind me asking, how often would you / the other occupants have a bath and at what time of day normally?
- Solar PV
 - Thinking about your use of appliances [refer to paper form if necessary]; what time of day do you use appliances most often now?
 - Has this changed since the panels were installed?
- MVHR
 - How noisy is this? [if noisy] What do you do to cope with this?
- Heat Pumps
 - Do you know what kind of electricity tariff you have?
 - Does it have Economy 7/10? If so, were the benefits of these types of tariffs explained to you?
- [for each measure **not** mentioned by the occupant(s)]
 - Apparently you also had < x > done to the property. Were you aware of this?
 - Yes - proceed to ask the questions above regarding this measure
 - No
- Finally, is there anything that you would have liked done to the house which has not been done?

QUANTITATIVE CODING:

Opinion of the measure	Very positive	Positive	Neutral (both positive and negative views)	Neutral (dis-interested)	Negative	Very negative
Quality of explanation	Excellent; occupant	Good	Mixed	Poor	Very poor; occupant(s)	

provided to the occupant of how the active measures work	Level of understanding of the purpose of the measure(s)	Excellent; occupant fully understood what the measure was designed to do and how it did it	Good	Mixed	Poor	did not know how the measures at all	
Level of understanding of what actions might affect measure performance	Level of understanding of what actions might affect measure performance	Excellent; occupant seemed fully aware of how their behaviour could affect measure performance	Good	Mixed	Poor	Very poor; occupant(s) did not understand how their behaviour might affect measure performance	
Level control (usage)	Level control (usage)	Full control	Good	Mixed	Poor	No control	

Post-installation experience

- Now that the work has been done, do you:
 - Prefer the property now - why?
 - Feel no different
 - Preferred the property as it was before the work was done - why?

- Have you noticed a change in your energy bills since the work was done? If so, please describe.
- Do you pay your own energy bills? If yes, what percentage of your weekly budget do they take up?
- Could you tell me which of these bands your household income fits into?
 - o £0 to £9,999
 - o £10,000 to £19,999
 - o £20,000 to £29,999
 - o £30,000 or above

QUANTITATIVE CODING:

Occupant opinions of the post-installation property	Very positive	Positive	Neutral (both positive and negative views)	Neutral (dis-interested)	Negative	Very negative
Level of occupant control of temperatures	Complete	Good	Some	Low	Little / none	

Behaviour change

- What are your views in general about being green and saving energy in the home?
 - How green do you think your general lifestyle is, on a scale of 1 to 5, 1 being not at all and 5 being very?
 - Would you say that your views changed as a result of experiencing this project? If so, where would you have rated yourself before the works were done?
- Has living in this property - with its improvements / added technology - made you think more about the amount of electricity and gas you are using in the house, whether through heating or appliance use?
 - i. If not, why not?

- ii. If so, what do you differently since the installation process? Why? How much has your life style changed? Can you give an example?
 - Do you know about the monitoring work that is going on?
 - [if unaware] Explain the monitoring.
 - [if aware] Has this affected your behaviour in any way?

QUANTITATIVE CODING:

Pre-installation level of occupant behaviour	Excellent	Good	Mixed	Poor	Very poor;
Post-installation level of occupant behaviour	Excellent	Good	Mixed	Poor	Very poor

Overall satisfaction with the process

- How satisfied were you with the process as a whole? By the process I mean the whole experience of what has happened to your home, the way you have been informed and the information, explanations and instructions you've been given. (show smiley face satisfaction scale and then probe on selection).
 - What, if anything, went particularly well?
 - What, if anything, did not go well? How do you think any aspect of the whole process could be improved for tenants like you?

QUANTITATIVE CODING:

Occupant opinion of the whole process	Very positive	Positive	Neutral (both positive and negative views)	Neutral (dis-interested)	Negative	Very negative
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- Do you / other occupants have any health problems?

Close interview

- Encourage them to complete forms if not done so.
- Explain when we might next be in touch and leave contact details for them.
- Thank them for their time and help.

Desirability

- Do you think that the work that has been done to your property is something that everyone would want?
 - Yes, why?
 - No, why not? Are there particular groups that would / wouldn't want it?
- Has anyone visited and commented on the things you have had done? What did they say about them? Did they like them?
- Do you feel the house is special in any way now that you have had the installations? Do you think friends / neighbours are impressed by your house?

QUANTITATIVE CODING:

Occupant perceptions of desirability	Highly desirable / viewed positively	Neutral / unsure	Not desirable / viewed negatively
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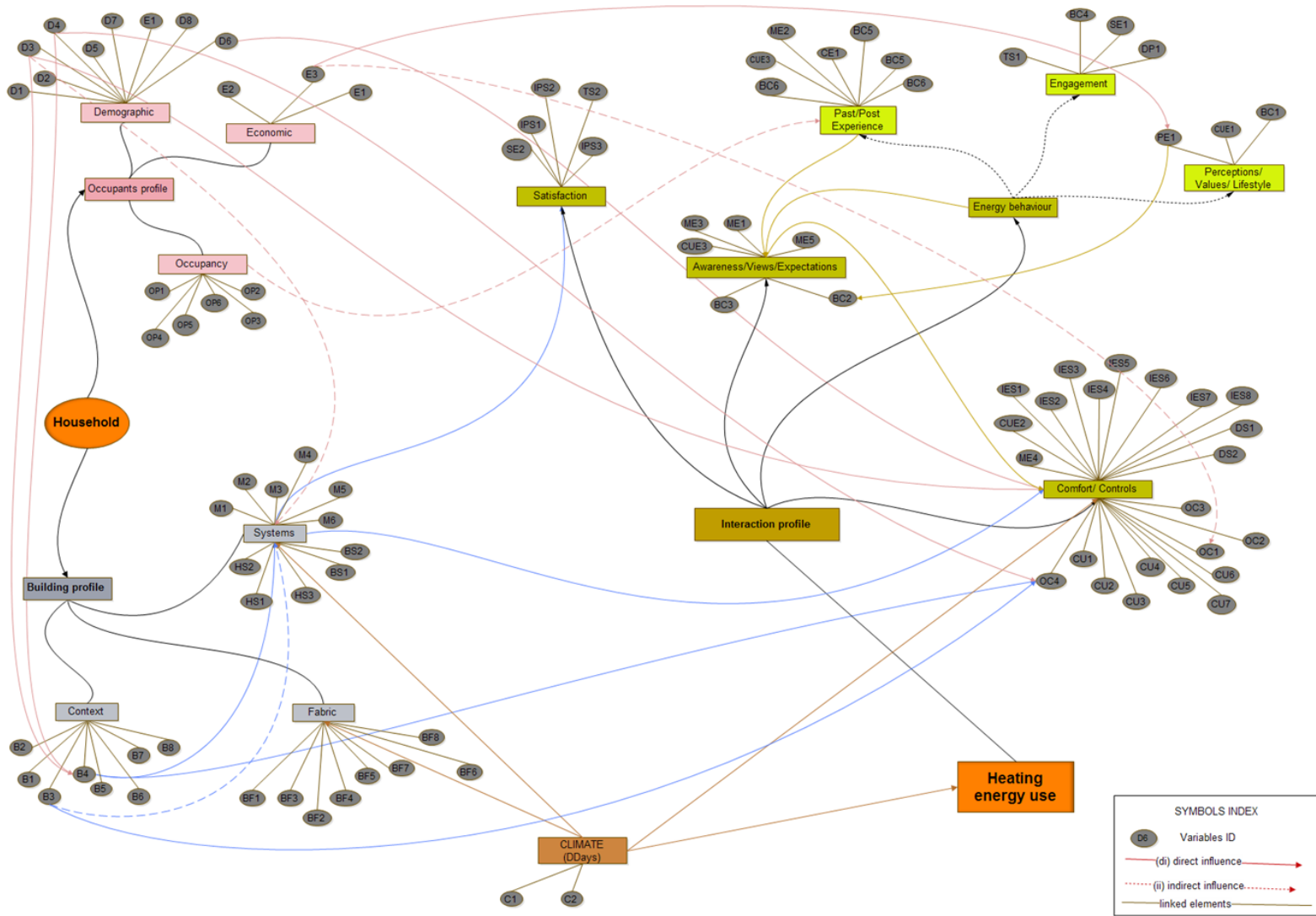
Final demographic questions

I would like to finish now with a couple of questions about day-to-day life in the house. This will help us to understand how much energy is used and when.

- What things do you think use most gas and electricity in your house? [IF PHYSICAL MONITORING DATA WERE AVAILABLE, THIS COULD BE EXPLORED AT THIS POINT].
- Does anyone in the house smoke at all? If so, do they do this outside / open a window?
- Do you or any of the other occupants work?
 - Yes - what do you / they do? Is this full / part time? Is it a fixed contract?
 - No
- Are you or any of the occupants away for long periods of time? e.g. students at university, people away with work. Are there times when the house has more or fewer occupants?

Appendix 12 Initial thematic map, variable correlations from the literature and preliminary analysis of the study's sample and (followed by variables index in next page).

(ID) VARIABLES INDEX	
Occupants profile	(D1) Occup.Num. (D2) Gender (D3) Age group (D4) Family composition (D5) Cultural background (D6) Health conditions (D7) Smoking (D8) Pets (E1) Education/ Qualifications (E2) Occupation (E3) Income (PE1) Bills payment
Occupancy	(OP1) Occupancy background (OP2) Relocated during works (OP3) Living period in RfF property (OP4) Average occupancy in typical Week (Mon-Fri) (OP5) Average occupancy per Weekends (Sut-Sun) (OP6) Average occupancy annually
Building/ Systems performance (Fixed)	(C1) Building Orientation (C2) External temperature (B1) Building Status (B2) Age (B3) Type (B4) Tot. floor area (B5) Storeys (B6) Number of rooms (B7) Space layout (B8) Extentions/porches/conservatories (BF1) External walls (BF2) Ext. Walls finish (BF3) Partition walls (BF4) Roof /Loft (BF5) Floors (BF6) Windows (BF7) External doors (BF8) External shading Devices (BF9) Level of intervention (HS1) Heating system (HS2) Heating space (HS3) Heating Hot water (M1) Condensing Boiler (M2) Solar panels (M3) MVHR/Fans (M4) Solar PV (M5) Sun pipe light (M6) Intelligent control systems
Systems/ measures' installation	(DF1) Design faults (IF1) Installation faults
Building/ Systems performance (Interactive)	(CU1) Natural ventilation Windows (Control and use Summer) (CU2) Natural ventilation Windows (Control and use Winter) (CU3) Natural ventilation Doors (Control and use) (CU4) Heating controls (CU5) Natural lighting controls (Control and use) (CU6) Mechanical ventilation (Control and use)
Past/Post-experience	(BC5) Pre-installation level of occupant EE behaviour (BC6) Post-installation level of occupant EE behaviour (CUE3) Understanding of previous heating controls (CUE1) Opinion of the property prior to installations
Satisfaction	(IES1) Property condition (IES2) Health effects from property conditions (IES3) Draughts (IES4) Damp/ mould/ internal air quality (IES5) Smell (IES6) Natural Light (IES7) Noise (IES8) Security (DS1) Overall design (DS2) Change room sizes (SE2) Satisfaction with the process (IPS1) Improvements designed, as build (IPS2) Process (duration/ disruption/ cleanliness) (TS2) Level of instruction Satisfaction level (IPS3) Overall satisfaction with the property after refurbishment
Comfort	(CUE2) Comfort level of the property prior to installation (OC1) Overall comfort (Temperature) (OC2) Overall comfort (To cool down) (OC3) Overall comfort (To warm up)
Engagement	(DP1) Tenants participation in design (SE1) Support of the RfF refurbishment process
Awareness/ Knowledge	(BC2) Awareness of energy of electricity and gas usage (BC3) Awareness of the retrofitting process (CUE3) Understanding of previous heating controls (TS1) Instructions/training (Type) (ME2) Training provided (measure) (ME3) Understanding purpose of the measure(s) (ME5) Understanding Actions affecting measure performance
Behaviour change	(BC1) Energy saving changes, Level of Green lifestyle (BC4) Behaviour change due to monitoring (ME1) Opinion of the measure (ME4) Level of control (usage) measures (CE1) Change in energy bills



Appendix 13 Thermal images of the building fabric elements before the low-carbon refurbishment works (secondary source: TSB/EST database).

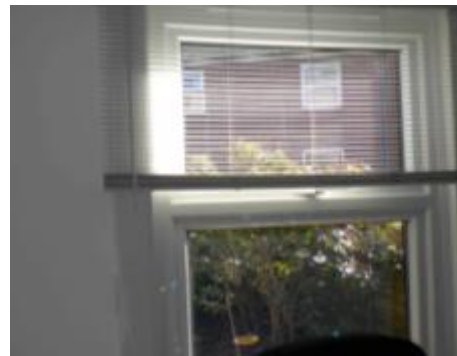
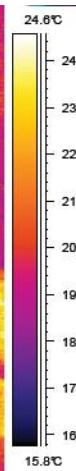


Figure 130: Thermal image of the window in the living room before the low-carbon refurbishment works.

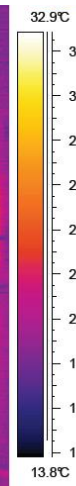
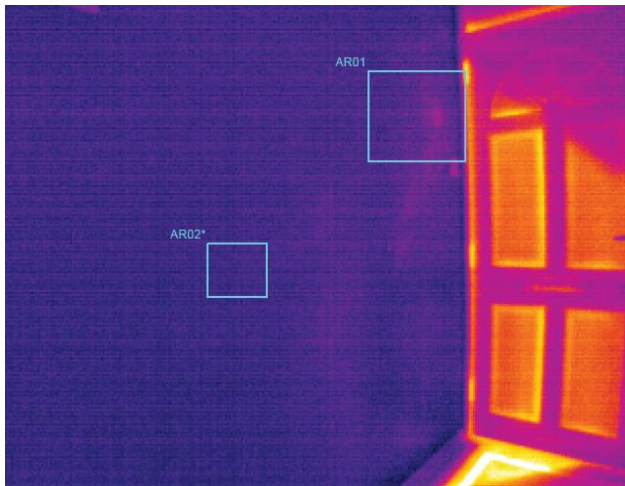


Figure 131: Thermal image of the main front entrance of the property before the low-carbon refurbishment works.

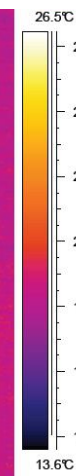


Figure 132: Thermal image of the window in the master bedroom.

Appendix 14 Figure 133: Gas consumption in kWh/day for the 9 months in 2011.

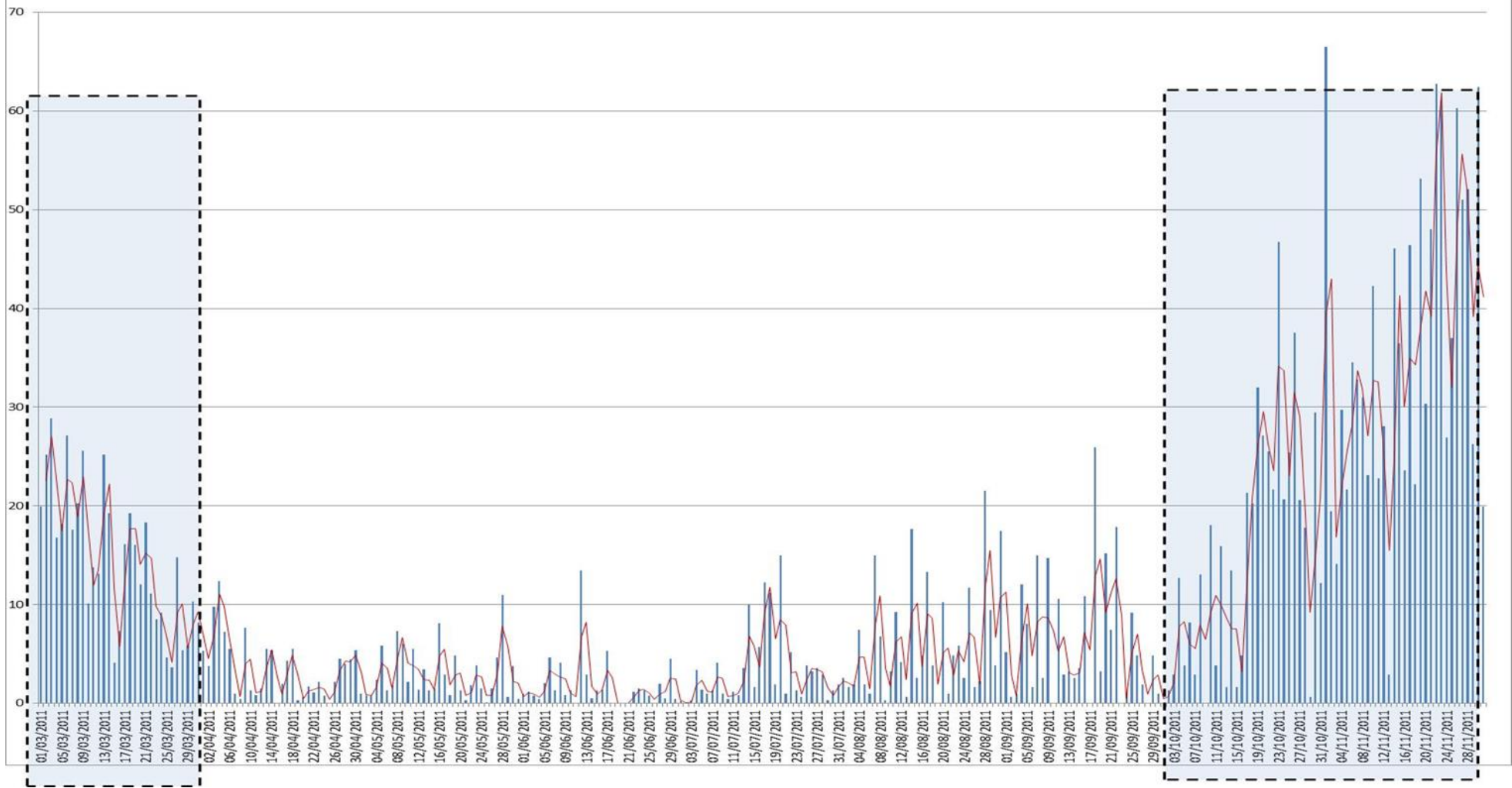


Figure 134: Electricity consumption for Feb to July 2012.

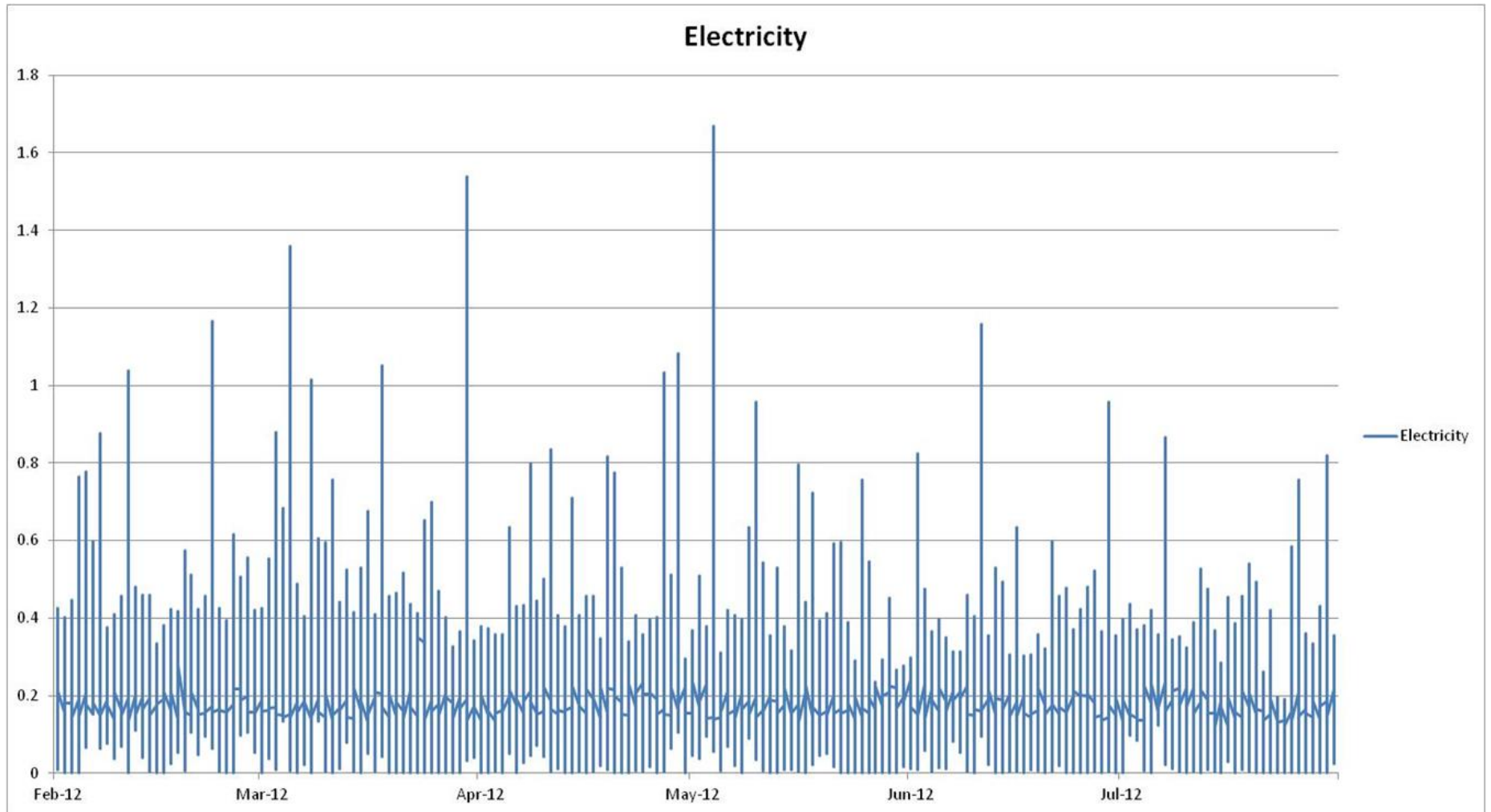
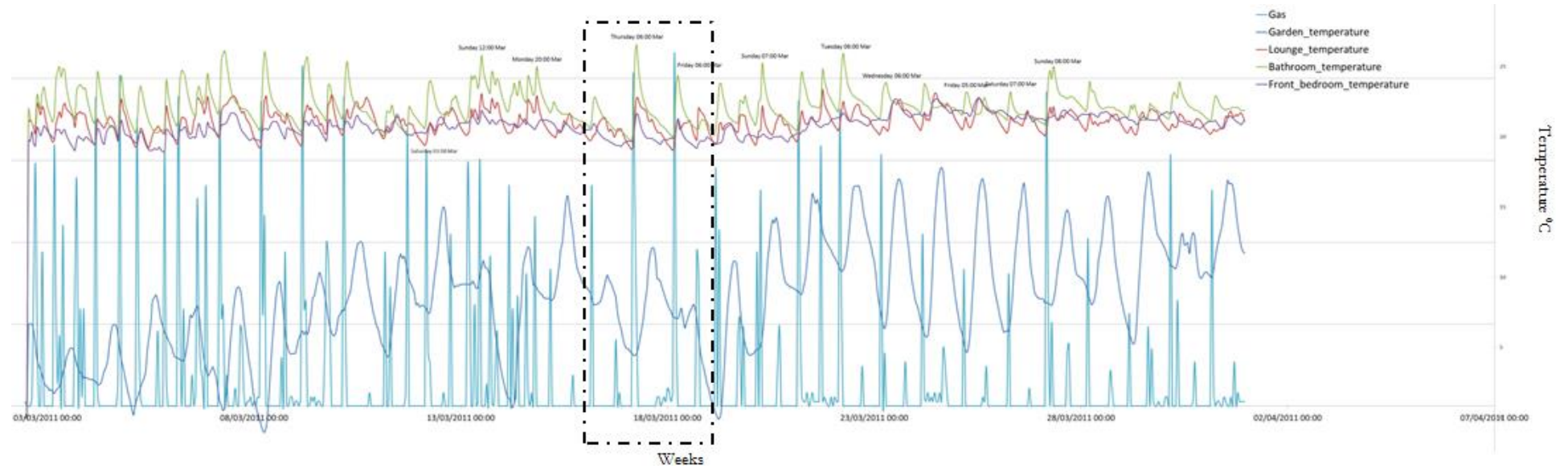
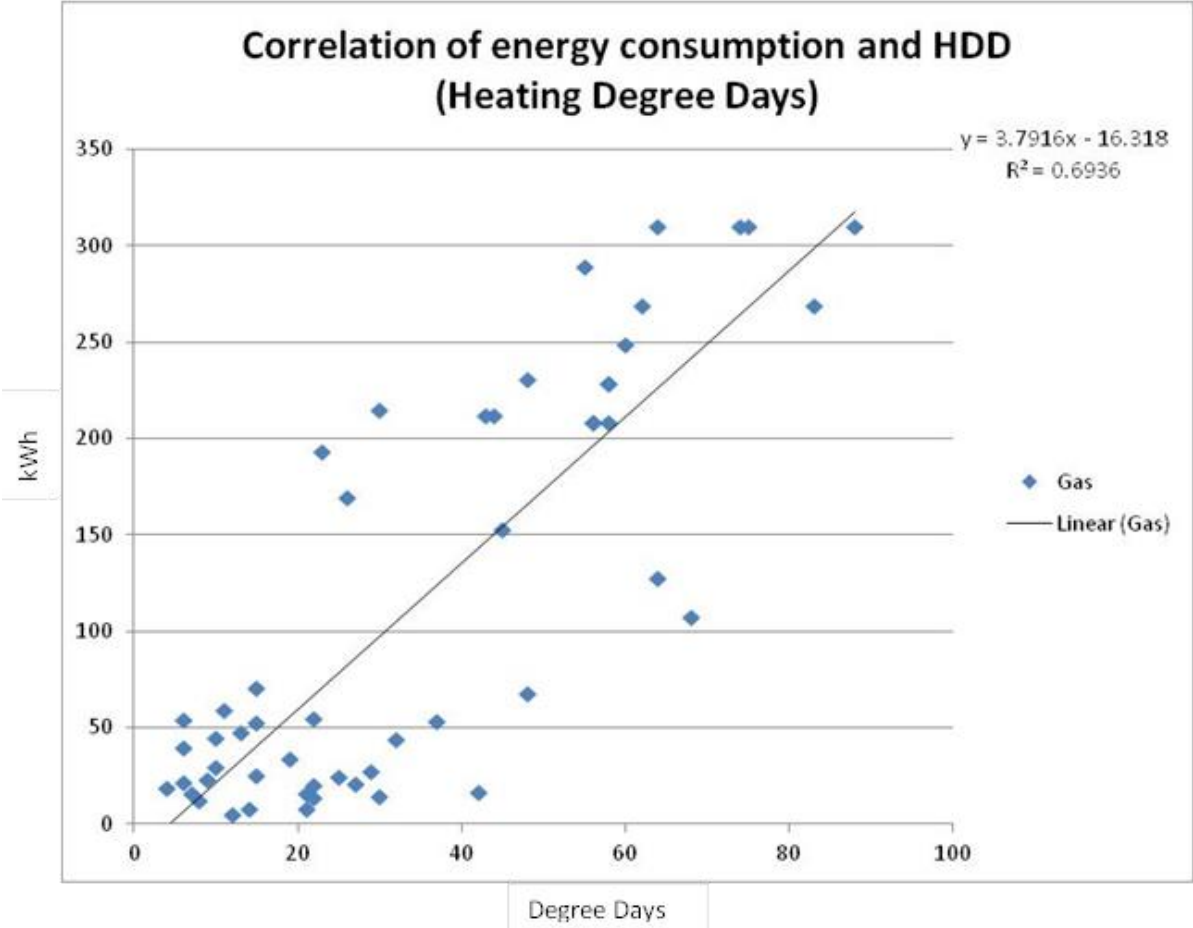


Figure 135: Gas consumption for the 9 months (2011) and external and internal temperature. Frequency of high temperatures in the bathroom, particularly in the morning hours, drops of the external temperature affect main bedroom temperature (dropping due to open window).



Appendix 15 Figure 136: Correlation of energy consumption and heating degree days.



Appendix 16 Physical measurements of indoor environment.

Figure 137: Internal, external temperatures and relative humidity in high occupancy rooms (month of July 2011).

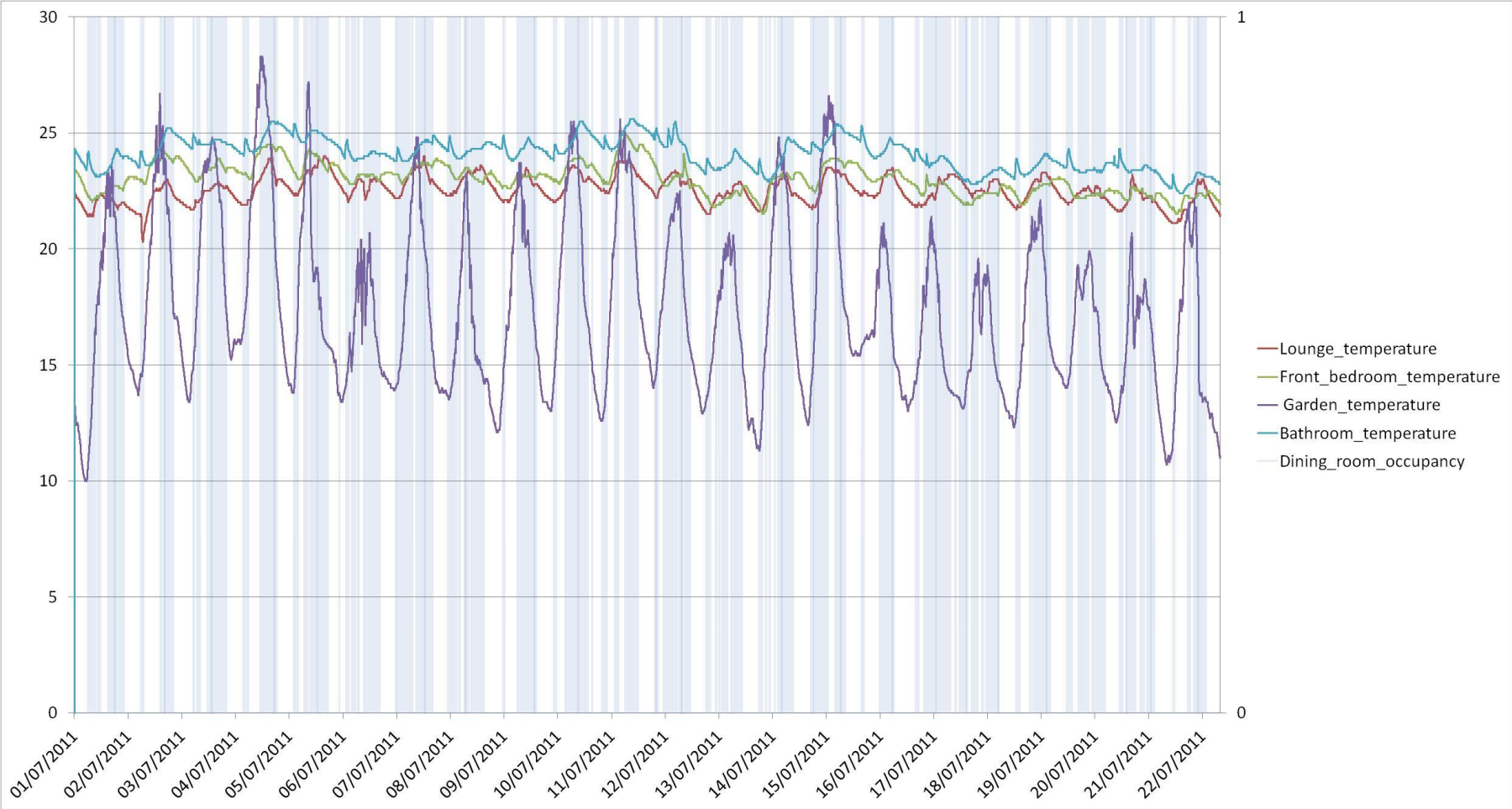


Figure 138: Internal, external temperatures and relative humidity in high occupancy rooms (month of October 2011).

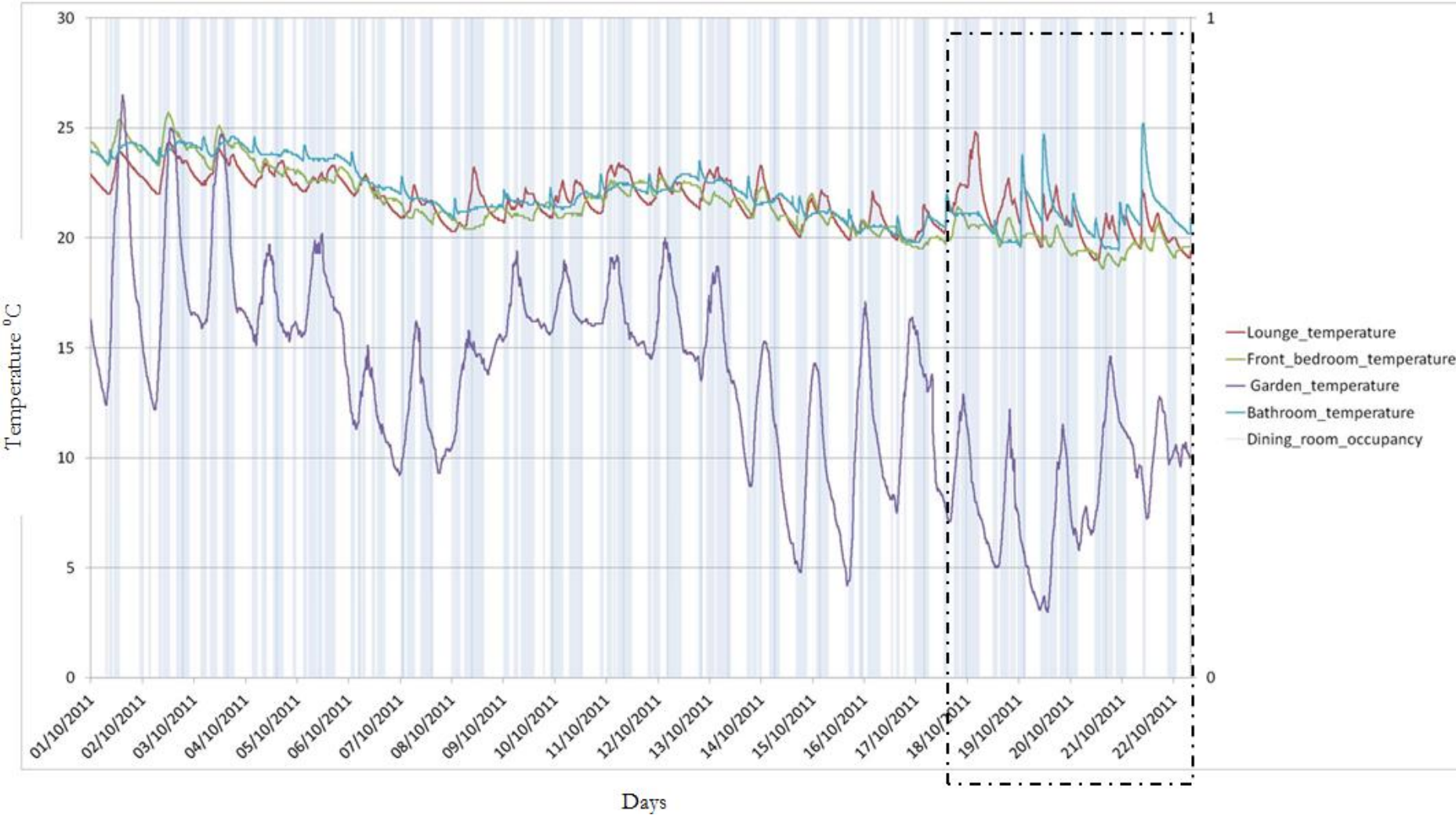


Figure 139: Internal and external temperatures and relative humidity for the month of September 2011.

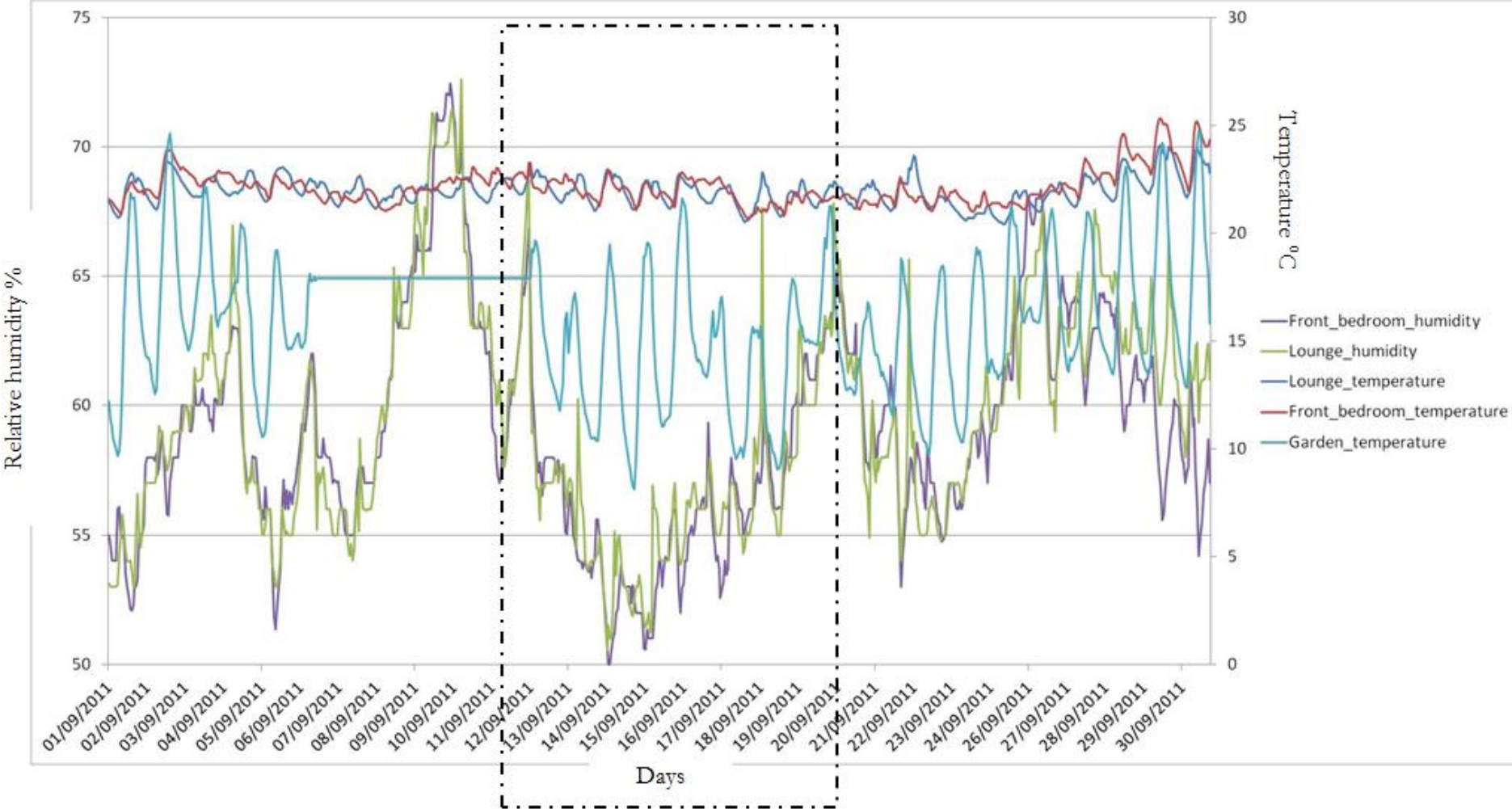


Figure 140: Relative humidity and CO₂ levels in high occupancy rooms for the month of September 2011.

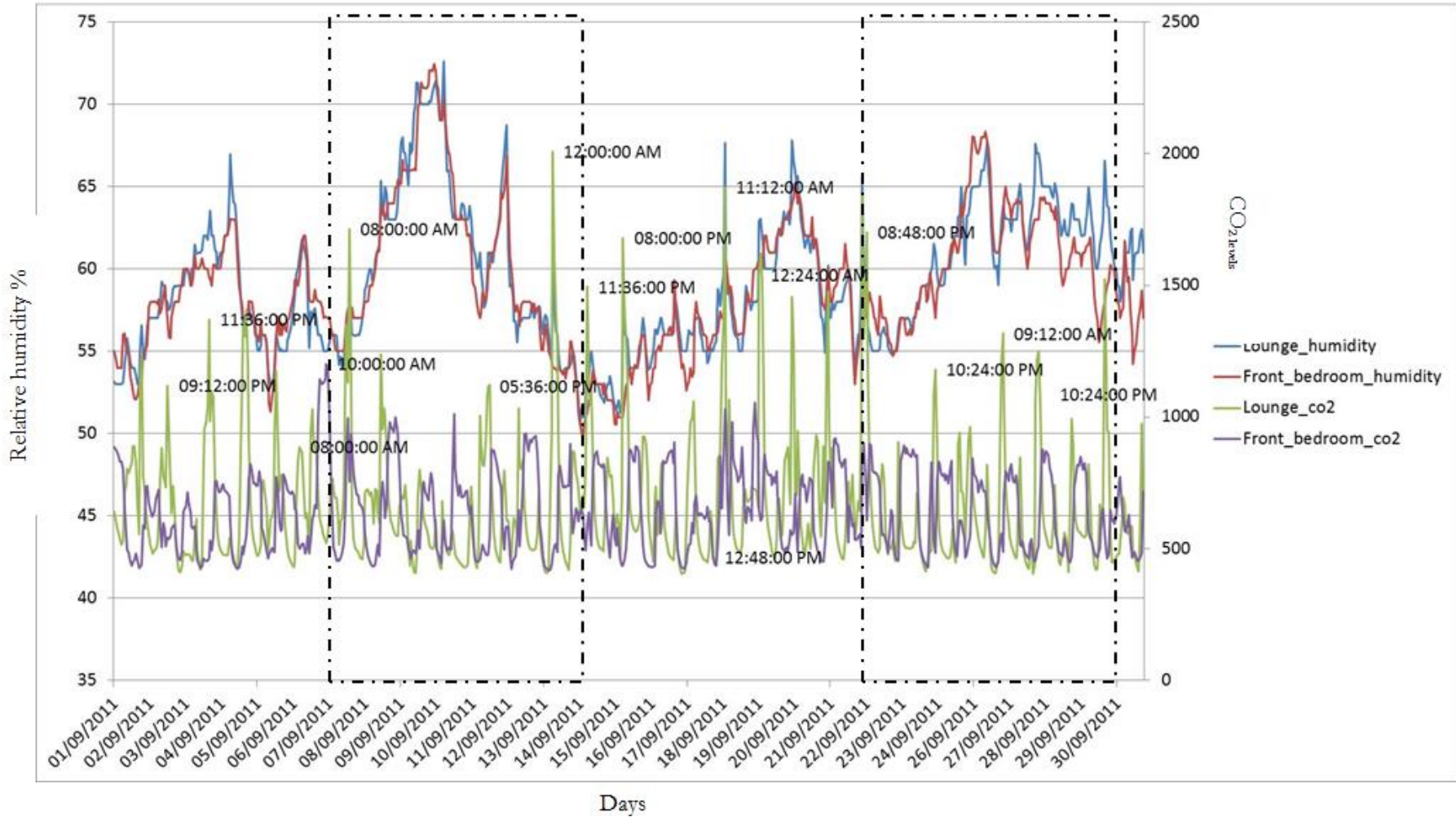


Figure 141: Relative humidity and CO₂ levels for the month of October 2011.

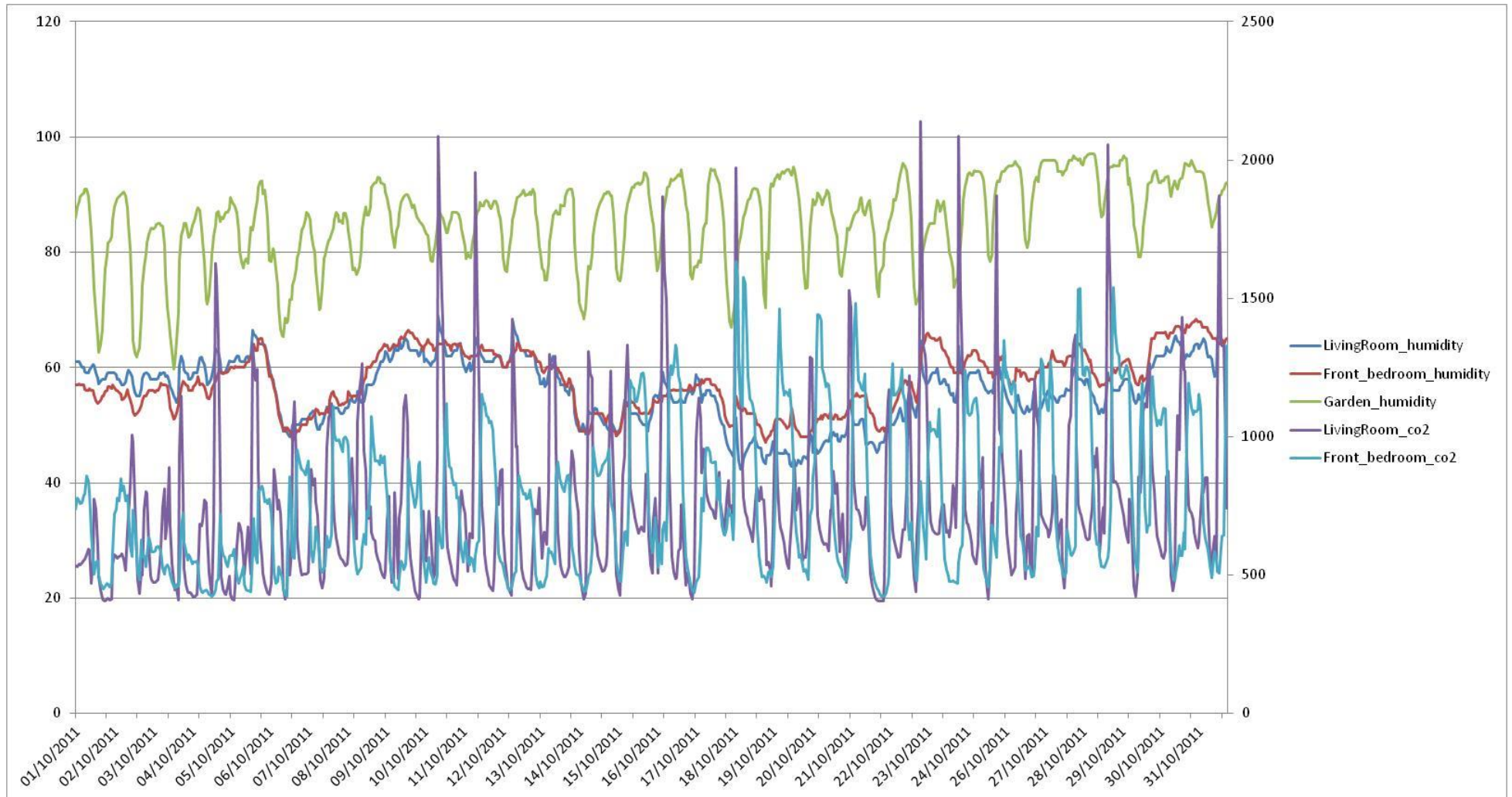


Figure 142: Relative humidity and CO2 levels in high occupancy rooms for the month of September 2011.

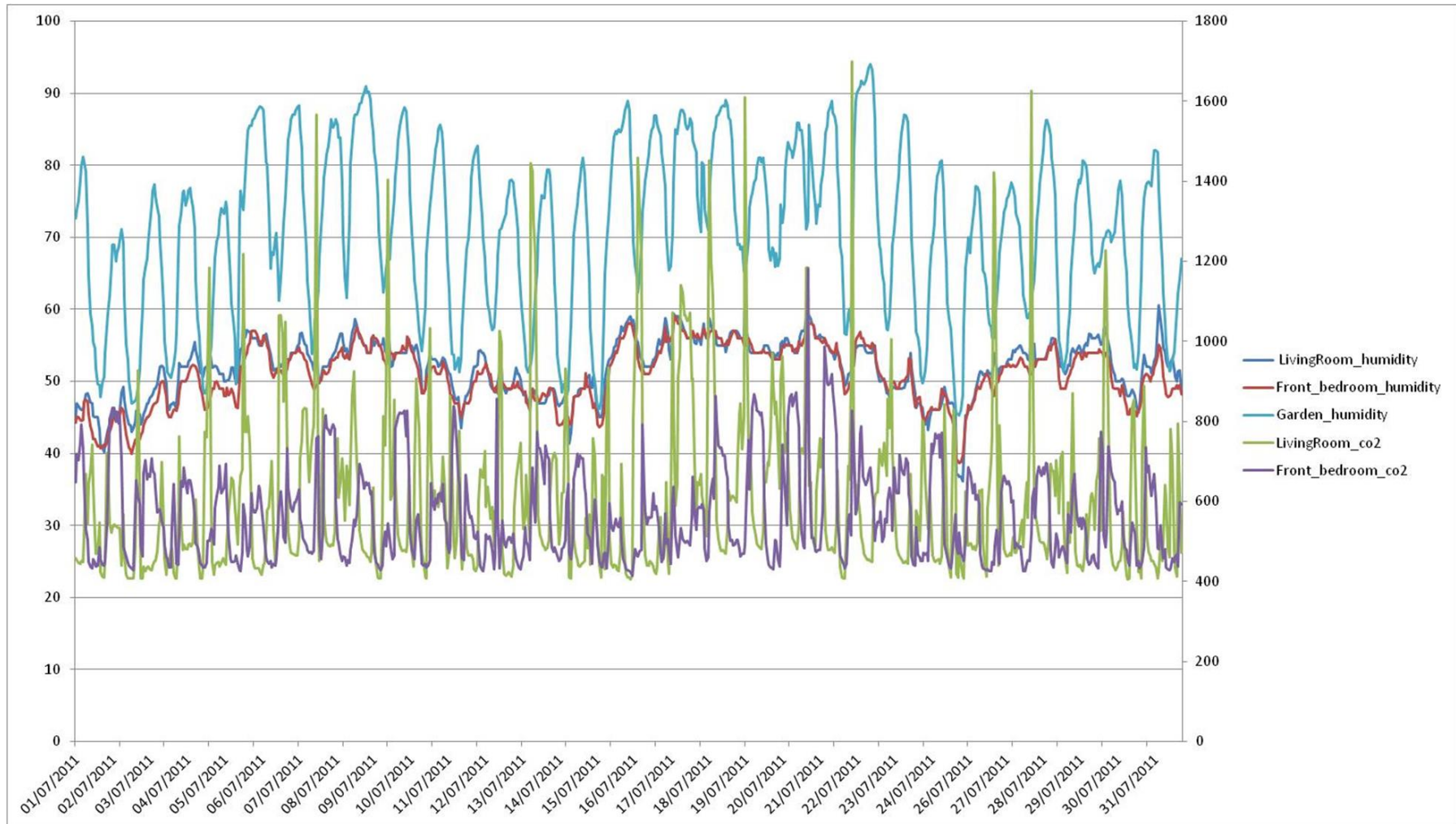
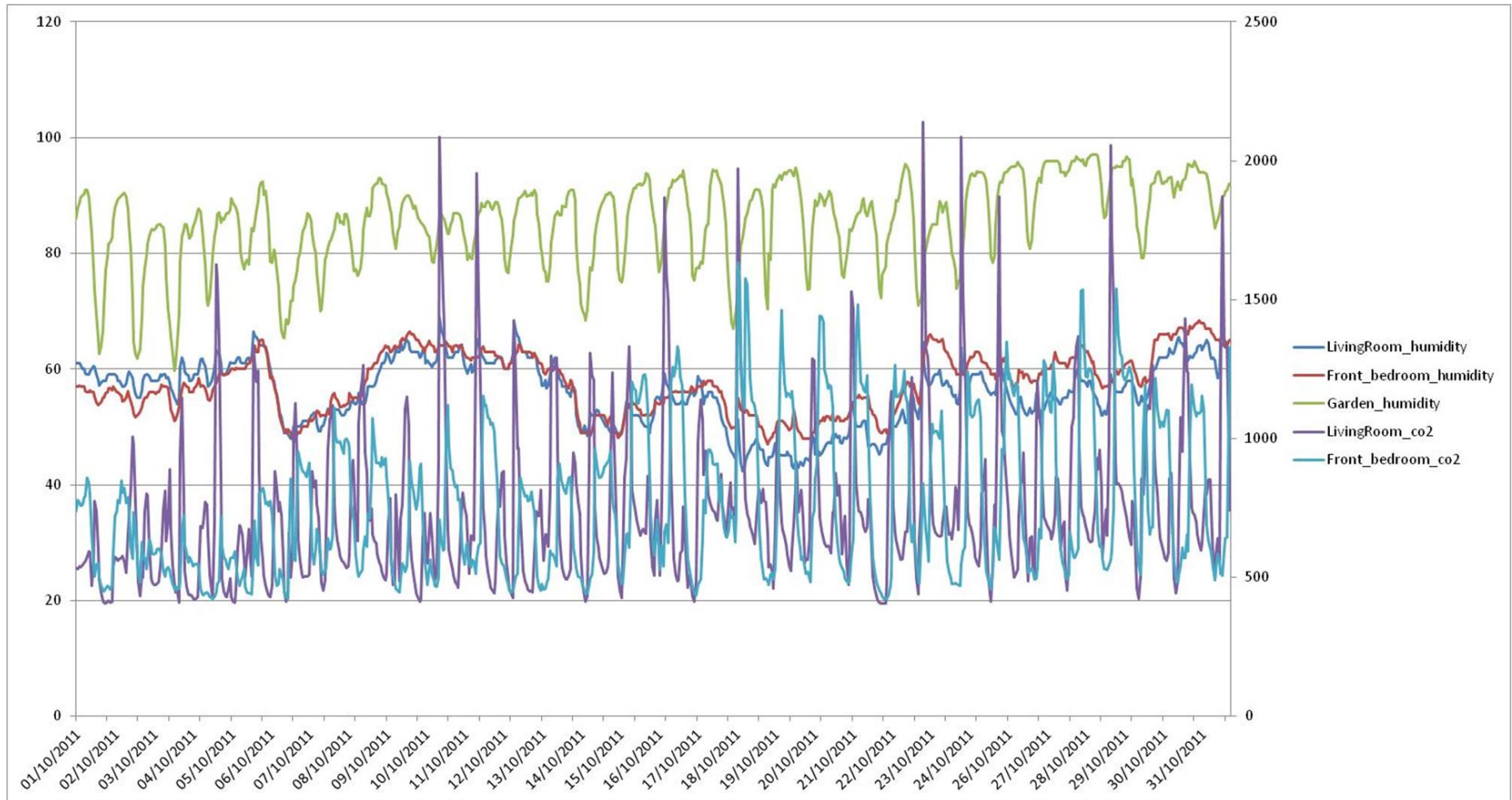



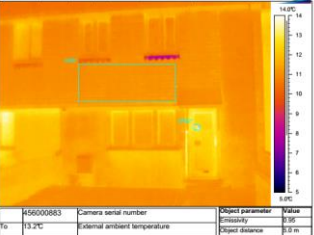




Figure 143: Relative humidity and CO2 levels for the month of October 2011.

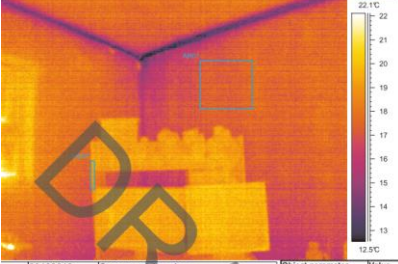

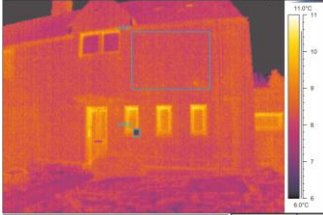





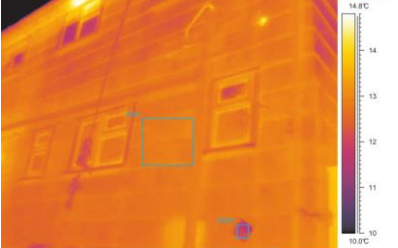





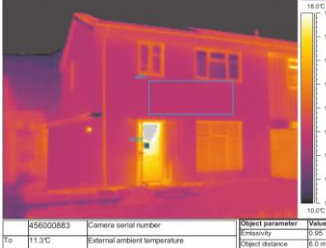



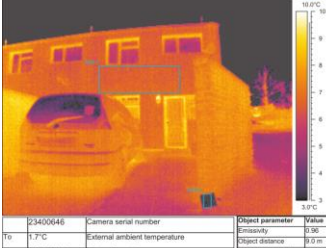

Appendix 17 Table 22: Outline of the key problems identified in the different stages

Pre-refurbishment		Post-refurbishment	
Design('as designed')		Installation	Operation (in-use)
Heating			
<i>Space</i>	Dependence on buildings' layout	Dependence on the performance of the building fabric and boiler system	Dependence on occupant behaviour and operation of heating controls and openings; on the arrangement of furniture (arm chair blocking radiator); Lack of understanding how heating is affected by passive and active ventilation
<i>Hot-water</i>	Lack of design guidance and experience of combined systems	Lack of experience in installing combined systems, dependence on different technical professions involved in the installation; performance not tested	Dependence on skills and support of the commissioned team; lack of understanding of how to use the combined system efficiently
Ventilation			
<i>Natural</i>	Dependence on conservation area's restrictions and buildings' form; window type does not take into account operation issues	Front window security issues not solved; poor installation of front and back door entrances	Dependence on occupant behaviour and operation (window type, size and design affecting occupant operation); lack of understanding of how passive and active ventilation affect one another
<i>Mechanical</i>	Lack of design of complex systems that include simple controls for the users	Lack of experience in installing	Lack of providing system controls for the MVHR, as well as lack of maintenance of the system, information and training

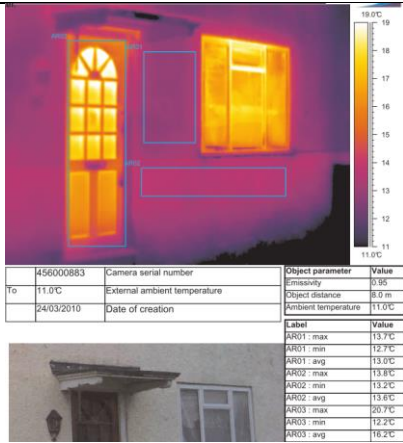
Appendix 18 Table 23: Thermal imaging analysis pictures pre and post-refurbishment.

TSB id	Pre-refurbishment	Post-refurbishment	Comments																																																																																								
TSB 044	 <table border="1"> <tr> <td>45600083</td> <td>Camera serial number</td> <td>Object parameter</td> <td>Value</td> </tr> <tr> <td>10.3°C</td> <td>External ambient temperature</td> <td>Emissivity</td> <td>0.93</td> </tr> <tr> <td>17/05/2010</td> <td>Date of creation</td> <td>Object distance</td> <td>31.0 m</td> </tr> <tr> <td></td> <td></td> <td>Ambient temperature</td> <td>10.3°C</td> </tr> <tr> <td></td> <td></td> <td>Label</td> <td>Value</td> </tr> <tr> <td></td> <td></td> <td>AR01 - max</td> <td>16.2°C</td> </tr> <tr> <td></td> <td></td> <td>AR01 - min</td> <td>10.4°C</td> </tr> <tr> <td></td> <td></td> <td>AR01 - avg</td> <td>12.1°C</td> </tr> <tr> <td></td> <td></td> <td>AR02 - max</td> <td>13.2°C</td> </tr> <tr> <td></td> <td></td> <td>AR02 - min</td> <td>7.8°C</td> </tr> <tr> <td></td> <td></td> <td>AR02 - avg</td> <td>10.3°C</td> </tr> </table>	45600083	Camera serial number	Object parameter	Value	10.3°C	External ambient temperature	Emissivity	0.93	17/05/2010	Date of creation	Object distance	31.0 m			Ambient temperature	10.3°C			Label	Value			AR01 - max	16.2°C			AR01 - min	10.4°C			AR01 - avg	12.1°C			AR02 - max	13.2°C			AR02 - min	7.8°C			AR02 - avg	10.3°C	 <table border="1"> <tr> <td>45600083</td> <td>Camera serial number</td> <td>Object parameter</td> <td>Value</td> </tr> <tr> <td>13.3°C</td> <td>External ambient temperature</td> <td>Emissivity</td> <td>0.93</td> </tr> <tr> <td>26/12/2011</td> <td>Date of creation</td> <td>Object distance</td> <td>30.0 m</td> </tr> <tr> <td></td> <td></td> <td>Ambient temperature</td> <td>10.3°C</td> </tr> <tr> <td></td> <td></td> <td>Label</td> <td>Value</td> </tr> <tr> <td></td> <td></td> <td>AR01 - max</td> <td>11.8°C</td> </tr> <tr> <td></td> <td></td> <td>AR01 - min</td> <td>10.0°C</td> </tr> <tr> <td></td> <td></td> <td>AR01 - avg</td> <td>10.2°C</td> </tr> <tr> <td></td> <td></td> <td>AR02 - max</td> <td>14.4°C</td> </tr> <tr> <td></td> <td></td> <td>AR02 - min</td> <td>10.3°C</td> </tr> <tr> <td></td> <td></td> <td>AR02 - avg</td> <td>13.4°C</td> </tr> </table>	45600083	Camera serial number	Object parameter	Value	13.3°C	External ambient temperature	Emissivity	0.93	26/12/2011	Date of creation	Object distance	30.0 m			Ambient temperature	10.3°C			Label	Value			AR01 - max	11.8°C			AR01 - min	10.0°C			AR01 - avg	10.2°C			AR02 - max	14.4°C			AR02 - min	10.3°C			AR02 - avg	13.4°C	<p>Pre-refurbishment:</p> <ul style="list-style-type: none"> - Air leakage around openings both (windows and doors) - Heat losses from window frame - Lack of insulation in the cladding <p>Post-refurbishment:</p> <ul style="list-style-type: none"> - Air leakage and heat losses improved - Cold bridge on the front window seal
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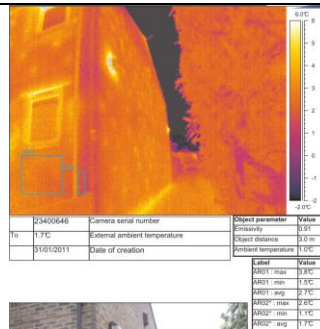
**TSB
033**



Pre-refurbishment:

- Air leakage around openings
- Heat losses from window frame and main door
- Lack of insulation and insulation defects in several parts of the walls
- Cold bridges on walls edges and between wall and roof

**TSB
076**

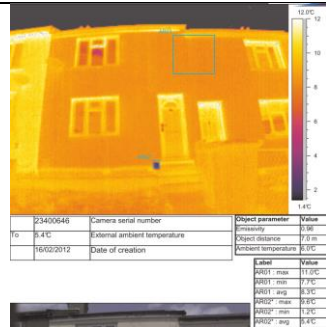
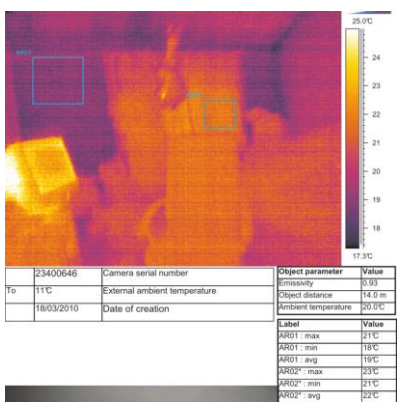
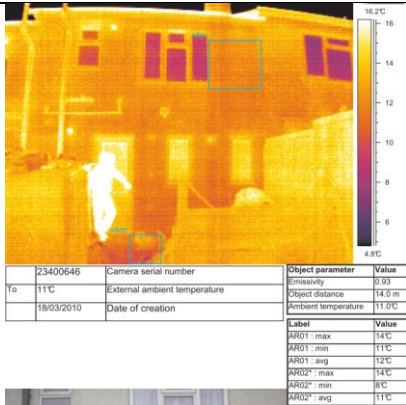


Post-refurbishment:

- Cold bridges on walls edges and between wall and roof
- Insulation defects on the walls

*The insulation was installed 3 years before the RfF project when in the estate retrofitting works were undertaken following the regulation standards. No further insulation improvements were undertaken by the RfF process for the walls in the property

**TSB
027**



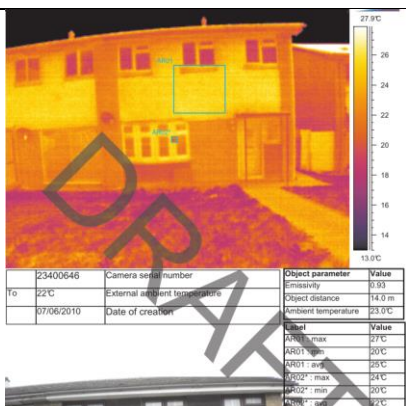
Pre-refurbishment:

- Air leakage around openings
- Heat losses from window frame
- Lack of insulation and insulation defects in several parts of the walls and cladding
- Cold bridges on walls edges and between wall and roof

Post-refurbishment:

- Air leakage and heat losses improved
- Minor insulation defects on the party wall with next building

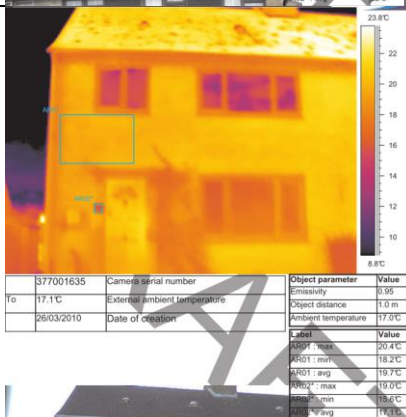
**TSB
113**



Pre-refurbishment:

- Air leakage around openings
- Lack of insulation and insulation defects in several parts of the walls and cladding

**TSB
002**



Pre-refurbishment:

- Air leakage around openings
- Lack of insulation and insulation defects in several parts of the walls and cladding
- Cold bridges on walls edges and between wall and roof

**TSB
110**

No data

Appendix 19 Table 24: Systems and measures controls ‘as designed’/ installed (n= 26 properties).

Systems’ direct or indirect operation via measures’ controls		Designed for ...	
Heating			
Space	Gas boiler:	<i>Direct:</i> via Gas boiler controls <i>Indirect:</i> via thermostat, programmer, TRVs	<i>Active users:</i> Gas boiler controls, Thermostat, Programmer, TRVs, Intelligent control systems (<i>Wattbox</i> , <i>Optima Design Controller</i>), wood-pellet boiler feeding system controls <i>Passive users:</i> CHP boiler controls, Heat pump boiler controls, Biomass controls, wood-pellet boiler feeding system controls, TRVs, MVHR air valves controls
	micro-CHP:	<i>Direct:</i> via CHP boiler controls <i>Indirect:</i> via Intelligent control systems (<i>Wattbox</i>), TRVs	
	Heat pumps:	<i>Direct:</i> via Heat pumps boiler controls <i>Indirect:</i> via Intelligent control systems (Optima Design Controller), MVHR air valves, <i>TRVs</i>	
	Biomass:	<i>Direct:</i> via Biomass controls, wood-pellet boiler feeding system controls <i>Indirect:</i> via thermostat, programmer, Intelligent control systems (<i>Wattbox</i>), TRVs	
	Thermal blinds:	<i>Direct:</i> via blind chain	
Hot water	Gas boiler:	<i>Direct:</i> via Gas boiler controls <i>Indirect:</i> via Programmer, Intelligent control systems (<i>Wattbox</i>)	<i>Active users:</i> Gas boiler controls, Programmer, Intelligent control systems (<i>Wattbox</i>), Wood-pellet boiler feeding system controls <i>Passive users:</i> CHP boiler controls, Heat pump boiler controls, Wood-pellet boiler feeding system controls, Solar thermal panel controls
	micro-CHP:	<i>Direct:</i> via CHP boiler controls <i>Indirect:</i> via Intelligent control systems (<i>Wattbox</i>)	
	Heat pumps:	<i>Direct:</i> via Heat pump boiler controls <i>Indirect:</i> via Intelligent control systems (<i>Wattbox</i>)	
	Biomass:	<i>Direct:</i> via micro-biomass controls, Wood-pellet boiler feeding system controls <i>Indirect:</i> via programmer, Intelligent control systems (<i>Wattbox</i>)	
	Solar thermal:	<i>Direct:</i> via Solar thermal panel controls <i>Indirect:</i> via Intelligent control systems (<i>Wattbox</i>)	

Ventilation			
Natural	Windows:	<i>Direct</i> via Window operation <i>Indirect:</i> via Window filter vents, Door operation	<i>Active users:</i> Window operation, Window filter vents, Door operation <i>Passive users:</i> Doors lower edge gap
	Doors:	<i>Direct</i> via Door operation <i>Indirect:</i> via Window operation, Doors lower edge gap	
Mechanical	MVHR:	<i>Direct:</i> via MVHR controls <i>Indirect:</i> via Control panel, Boost button, MVHR air valves controls, Window & Door operation	<i>Active users:</i> Control panel, Boost button, MVHR air valves controls, Fan ON/OFF switch <i>Passive users:</i> MVHR controls, Fan & light one switch control, Window & Door operation
	MEV fans:	<i>Direct:</i> via Fan ON/OFF switch <i>Indirect:</i> via Fan & light one switch control, Window & Door operation	



Figure 144: Domestic biomass boiler (indoor living room) (TSB087).



Figure 145: Domestic biomass boiler (TSB002).



Figure 146: Air source heat pump (Nilan VP18 compact heat pump ASHP for Ventilation with heat recover, space heating and domestic hot water production), TSB031.



Figure 147: Air to air source heat pump (Daikin), TSB097.

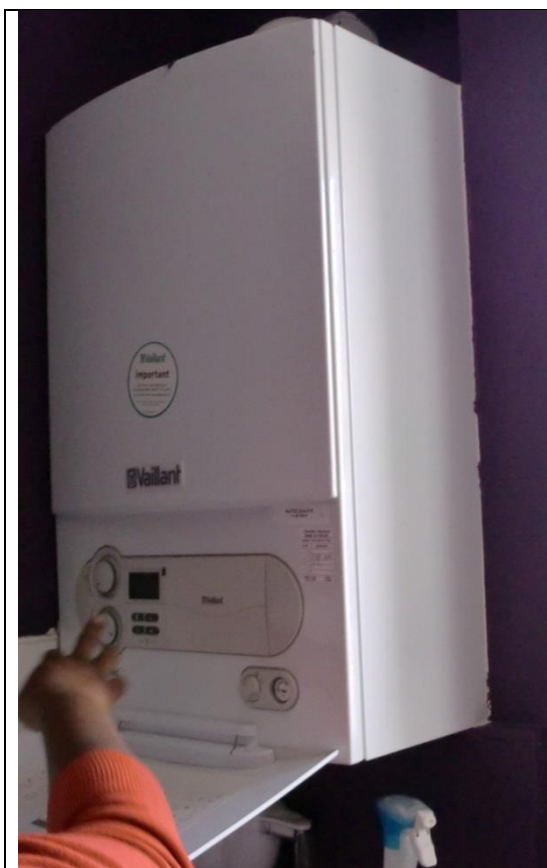


Figure 148: Combi gas boiler (ecoTec plus Vaillant) (TSB117).



Figure 149: Condensing gas boiler (Alpha CD12S) (TSB027).



Figure 150: Combi gas oiler (Worcester Greenstar 25Si) (TSB113 and 098).

Heating controls



Figure 151: Heating controls on the Combined Heat and Power (Baxi ECOGEN micro-CHP) (TSB034).



Figure 152: Heating controls on the Combined Heat and Power (Baxi ECOGEN micro-CHP) (TSB100).



Figure 153: Heating controls on the Ground Source Heat Pump boiler (GSHP) (TSB076).



Figure 154: Heating controls on the Air Source Heat Pump boiler (ASHP) (TSB033).



Figure 155: Heating controls on the domestic biomass boiler (TSB87).



Figure 156: Heating controls on the domestic biomass boiler (TSB002).



Figure 157: Heating controls on the domestic biomass boiler (TSB068,069).



Figure 158: Controls on the gas boiler heating system.



Figure 159: Controls on the gas boiler heating system.



Figure 160: Controls on the gas boiler heating system.

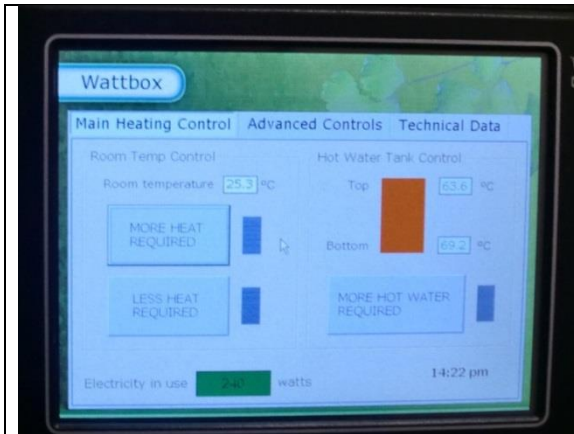


Figure 161: Case TSB044 Wattbox heating controller, room temperature indication 25.3 °C (26/01/2011, during POE walk-through).

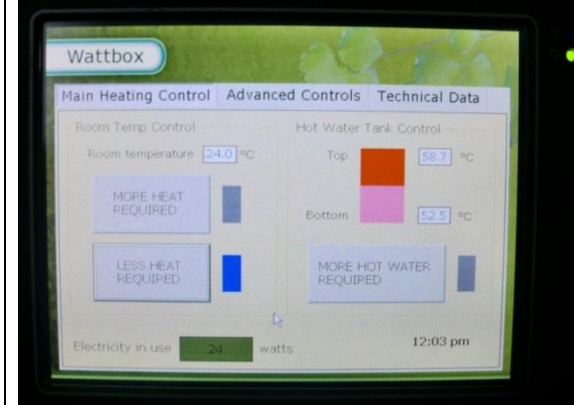


Figure 162: Case TSB047 Wattbox heating controller, room temperature indication 24 °C (28/11/2011, during POE walk-through).

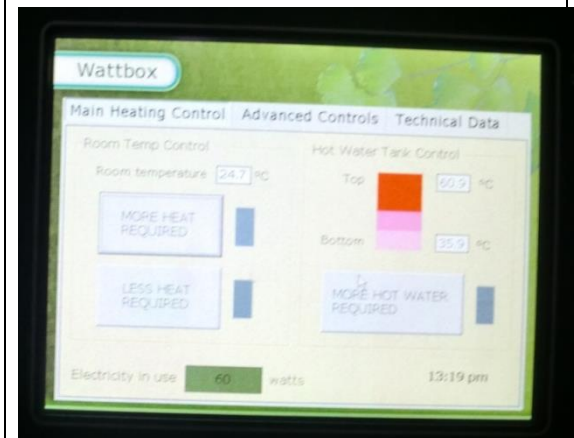


Figure 163: Case TSB041 Wattbox heating controller, room temperature indication 24.7 °C (10/12/2011, during POE walk-through).

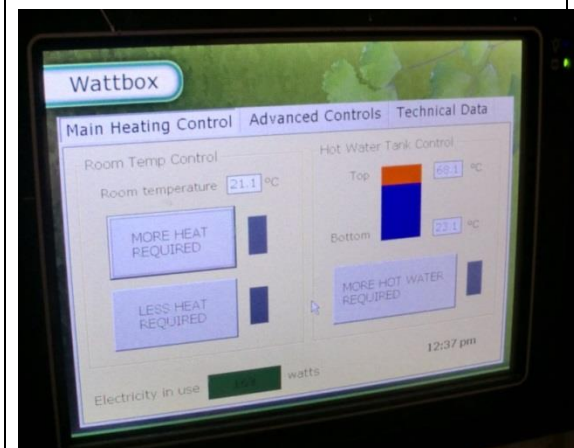


Figure 164: Case TSB040 Wattbox heating controller, room temperature indication 21.1 °C (13/02/2012) during POE walk-through).

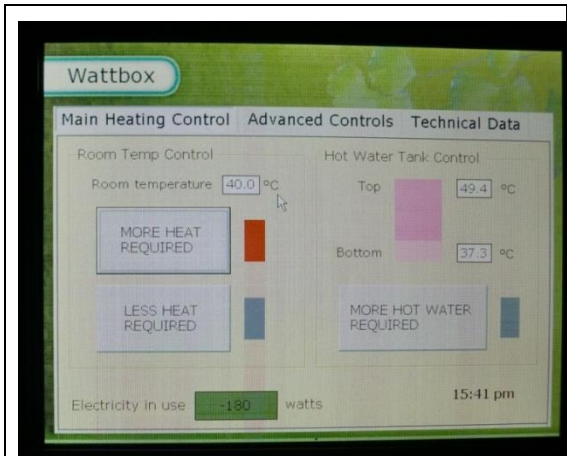


Figure 165: Case TSB042 Wattbox heating controller, room temperature indication 40 °C (10/12/2011, during POE walk-through – not working properly as the monitoring measurements have captured ground floor temp. 19.1 °C and 1st floor 19.7 °C).

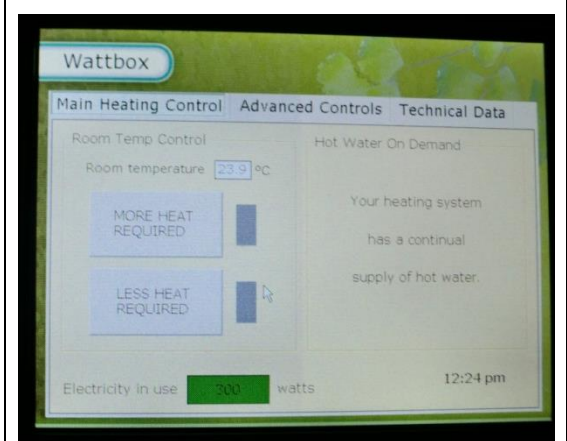


Figure 166: Case TSB036 Wattbox heating controller, room temperature indication 23.9 °C (11/10/2011, during POE walk-through).

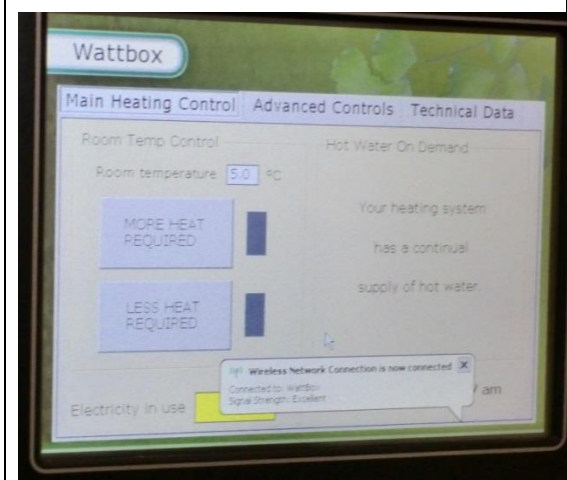


Figure 167: Case TSB033, Wattbox heating controller, room temperature indication 5 °C (26/01/2012, during POE walk-through - not communicating with the ASHP boiler).

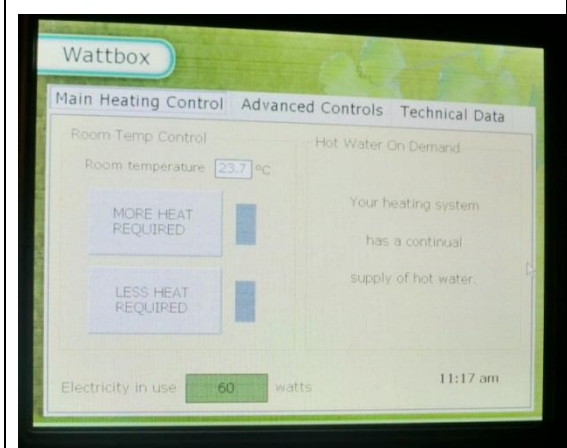


Figure 168: Case TSB076, Wattbox heating controller, room temperature indication 23.7 °C (24/11/2011, during POE walk-through- not communicating with the GSHP boiler).

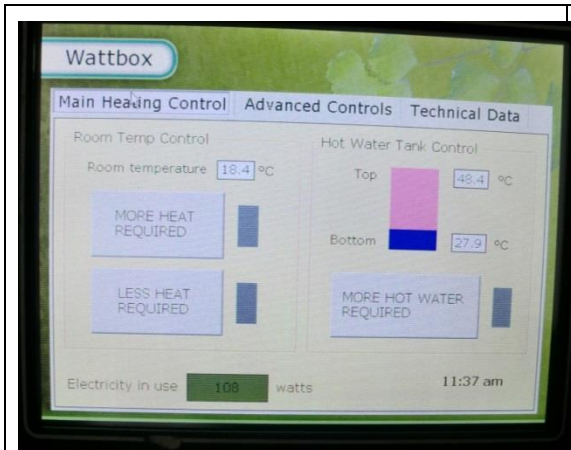


Figure 169: Case TSB087, Wattbox heating controller, room temperature indication 18.4 °C (09/03/2012, during POE walk-through).

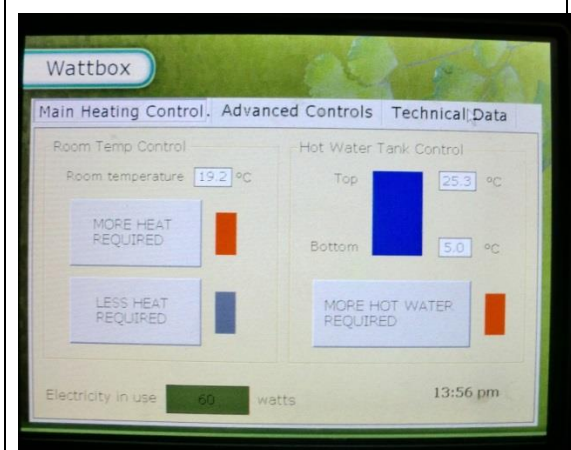


Figure 170: Case TSB100, Wattbox heating controller, room temperature indication 19.2 °C (09/03/2012, during POE walk-through).

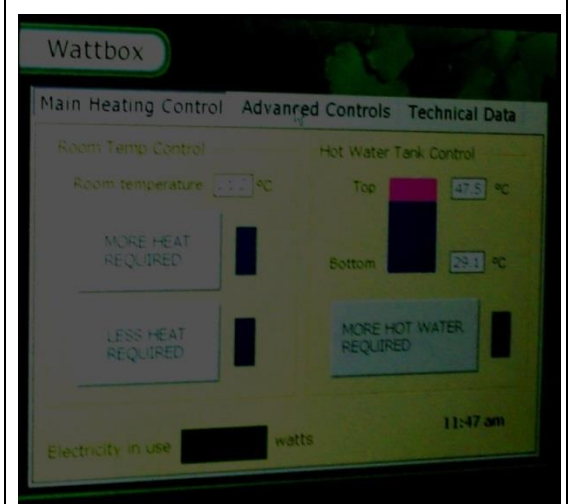


Figure 171: Case TSB034, Wattbox heating controller, room temperature indication 21 °C (08/09/2011, during POE walk-through).



Figure 172: Case TSB110, heating programmer, room temperature indication 22.8 °C (13/10/2011) during POE walk-through.

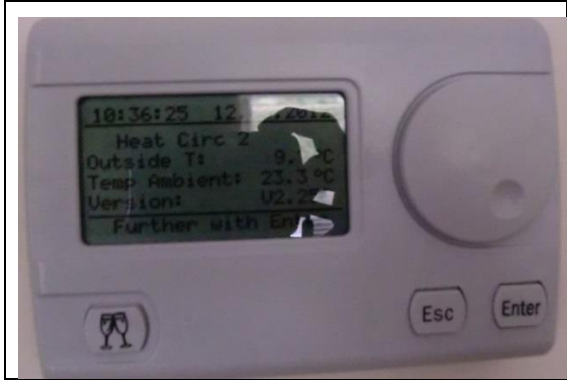
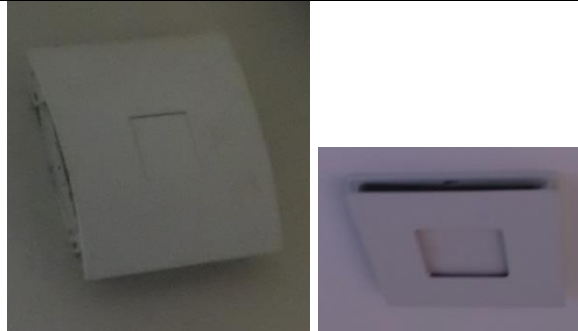










Figure 173: Case TSB022 heating programmer, room temperature indication 23.3 °C (12/03/2012) during POE walk-through.

Mechanical ventilation with heat recovery (MVHR)	
	<p><i>Figure 174: Ceiling or wall mounted air valves (designed not to allow direct interaction).</i></p>
	<p><i>Figure 175: Ceiling or wall mounted air filter (designed not to allow direct interaction)</i></p>
	<p><i>Figure 176: Ceiling or wall mounted air filter (designed not to allow direct interaction).</i></p>
	<p><i>Figure 177: Wall mounted air filter (designed not to allow direct interaction).</i></p>
	<p><i>Figure 178: Wall mounted air filter (designed not to allow direct interaction).</i></p>
	<p><i>Figure 179: Ceiling or wall mounted air valves (designed to allow direct interaction).</i></p>

Mechanical exhaust ventilation (MEV) and conventional fans		
		<p><i>Figure 180: Wall mounted air filter (designed not to allow direct interaction).</i></p>
		<p><i>Figure 181: Ceiling mounted vent fan (designed to allow direct interaction).</i></p>
Other measures installed		
		<p><i>Figure 182: Case TSB027, 031, 044 and 054, sunpipe installed in the staircase area to improve natural light and natural ventilation.</i></p>

Monitoring tools	
	<p><i>Figure 183: Monitoring web interface tool of the electricity generation.</i></p>
	<p><i>Figure 184: Green Energy Options Trio, real time energy display monitoring energy consumption for the 'whole house' and individual appliances.</i></p>
	<p><i>Figure 185: Green Energy Options Trio, real time energy display monitoring energy consumption for the 'whole house' and individual appliances.</i></p>
	<p><i>Figure 186: iEi touch screen monitoring display real time energy display monitoring energy consumption for the 'whole house' and individual appliances.</i></p>



Figure 187: Monitoring display real time energy display monitoring energy consumption for the 'whole house' and individual appliances.

Intelligent heating controls

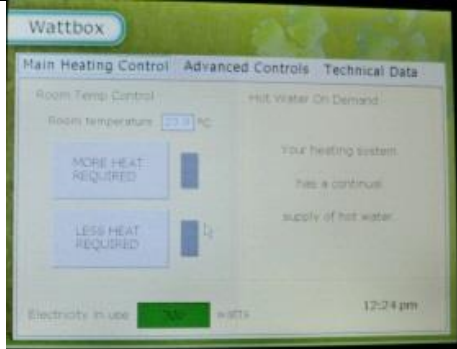


Figure 188: Wattbox intelligent controller.



Figure 189: Genvex Optima Design Controller (for heat recovery and heat pump ventilation appliances).



Figure 190: Intelligent TRVs (thermostatic radiator valves) with control settings.

Conventional heating controls



Figure 191: Programmer in ASHP system.



Figure 192: Convectional programmer.



Figure 193: Convectional programmer.



Figure 194: Convectional programmer.



Figure 195: Convectional programmer.



Figure 196: Digital thermostat.



Figure 197: Digital thermostat.



Figure 198: Digital thermostat.



Figure 199: Thermostat.



Figure 200: Convectional TRV thermostatic radiator valves).



Figure 201: Convectional TRV thermostatic radiator valves).



Figure 202: Thermo skirting heaters controls.



Figure 203: Storage heaters controls.



Figure 204: Storage heaters controls.



Figure 205: Storage heaters controls.



Figure 206: Solar thermal controls.

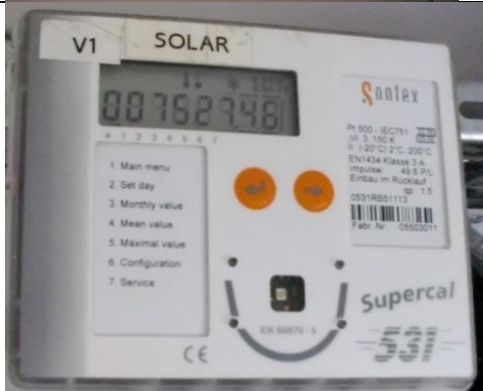
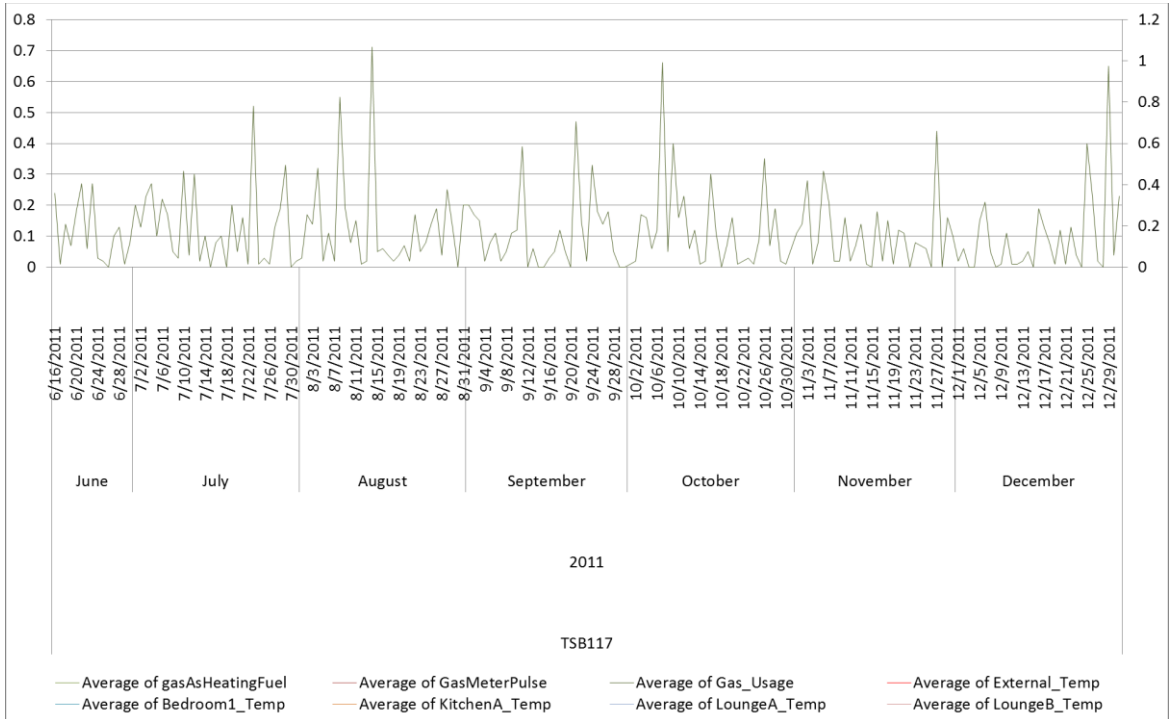
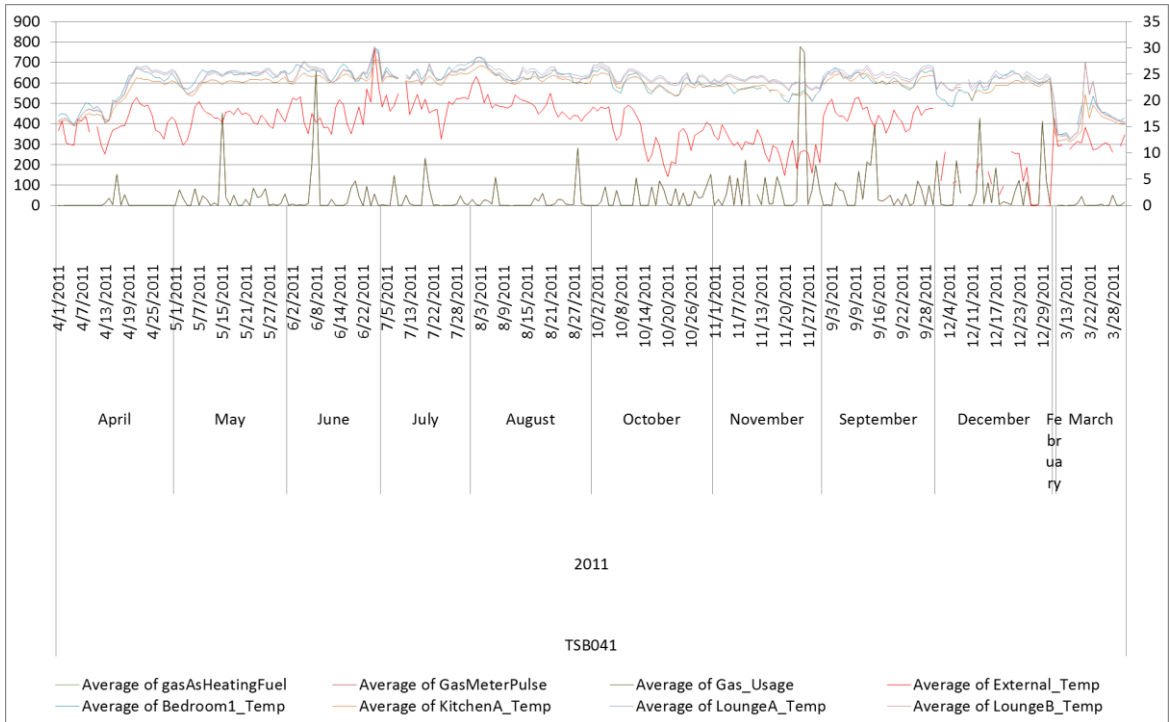
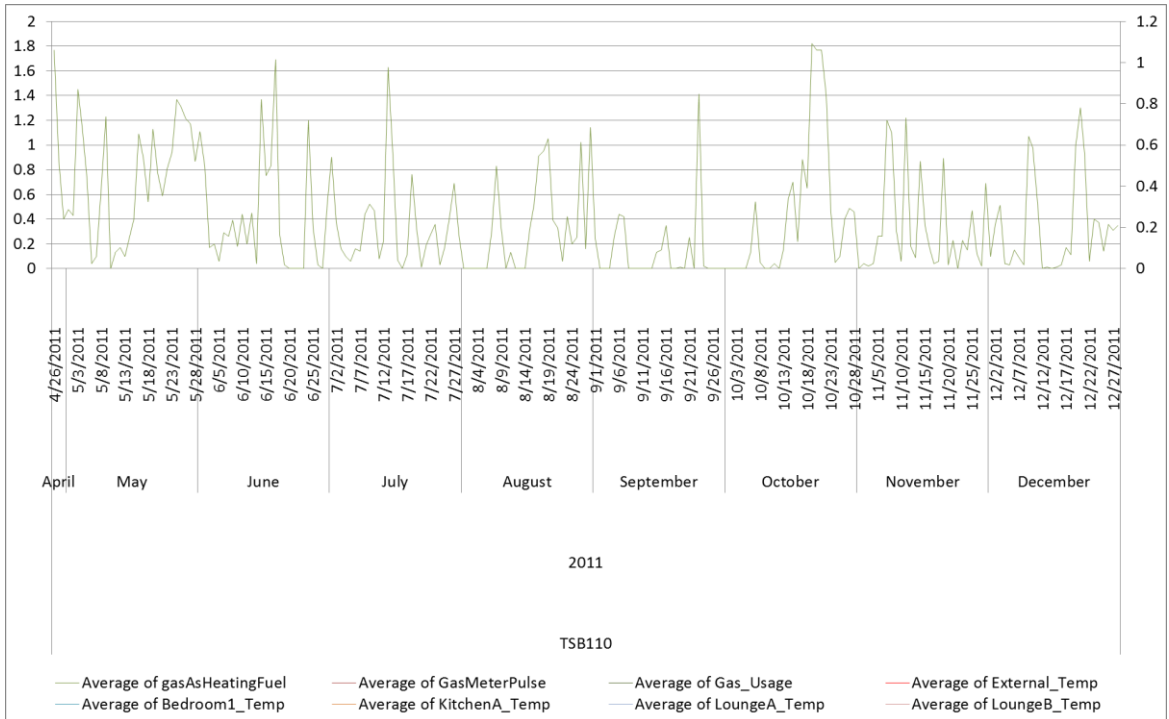


Figure 207: Solar thermal controls.

Appendix 23 Figure 208: Gas consumption of cases with CHP (TSB041) and boiler (TSB110 and 117) heating system. Instant peaks of consumption confirm occupants' sayings of malfunction of the heating system.





Appendix 24 Figure 209 Energy performance line for cases with gas boiler heating system. In TSB025, poor correlation of energy consumption and heating degree days was found.

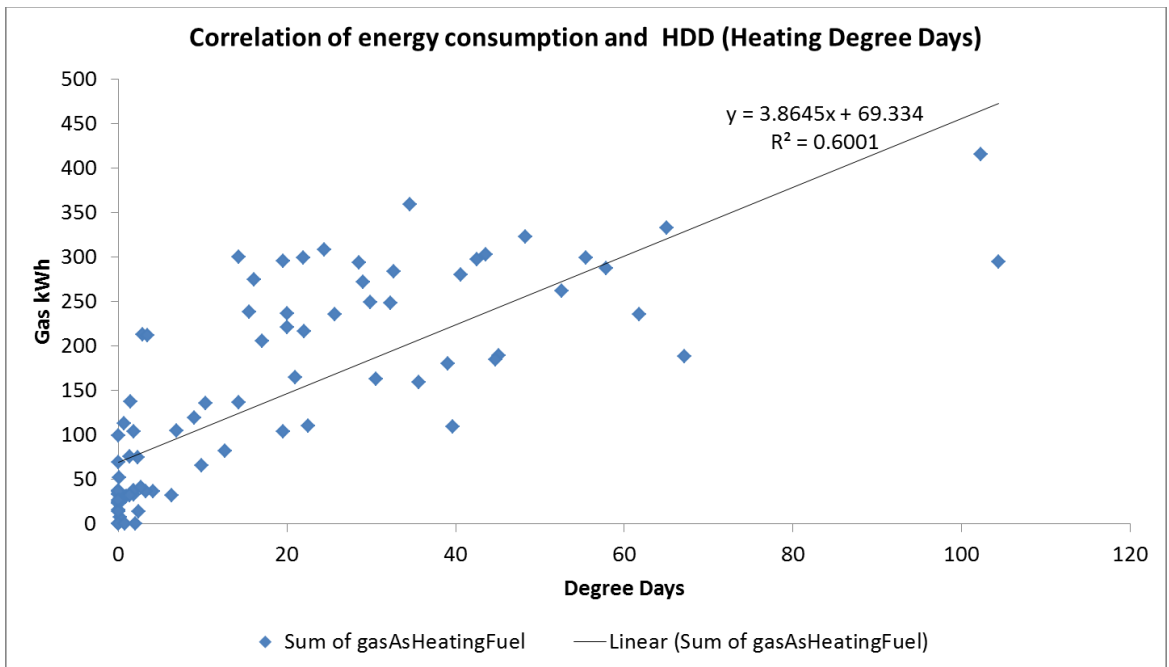


Figure 210: Energy performance line for cases with gas boiler heating system. In TSB027, poor correlation of energy consumption and heating degree days was found.

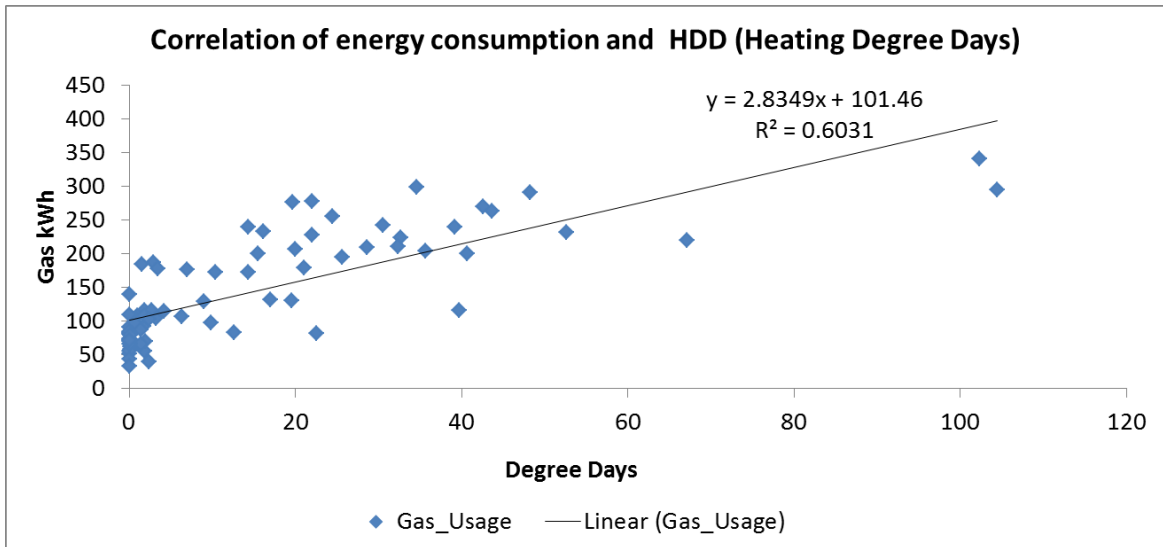


Figure 211: Energy performance line for cases with gas boiler heating system. In TSB054, poor correlation of energy consumption and heating degree days was found.

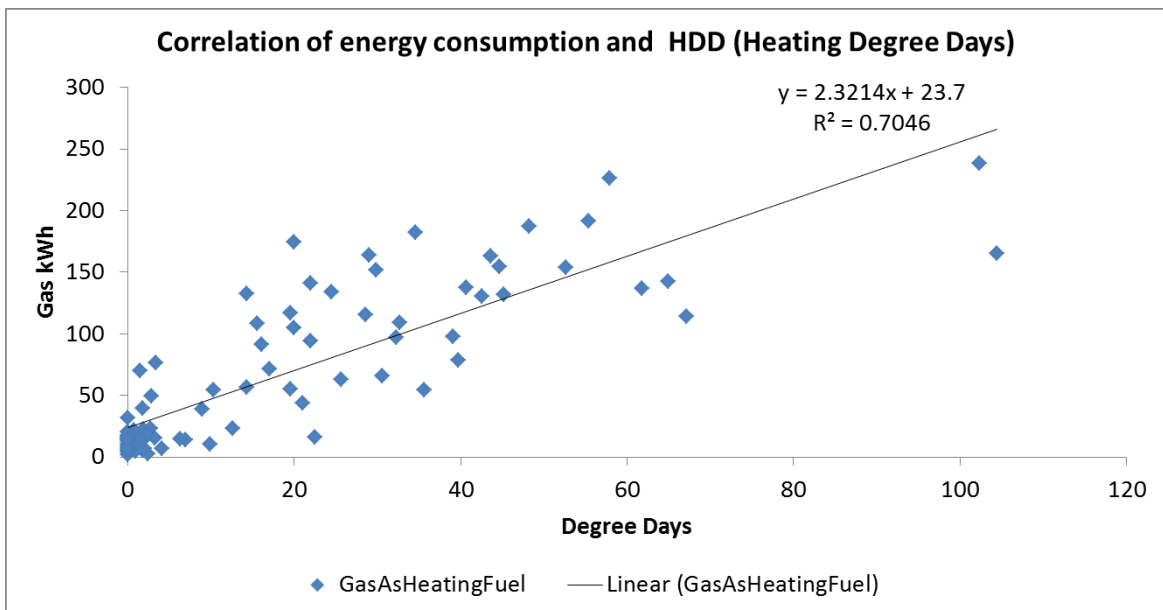


Figure 212: Energy performance line for cases with gas boiler heating system. In TSB110, very poor correlation of energy consumption and heating degree days and lack of data was found.

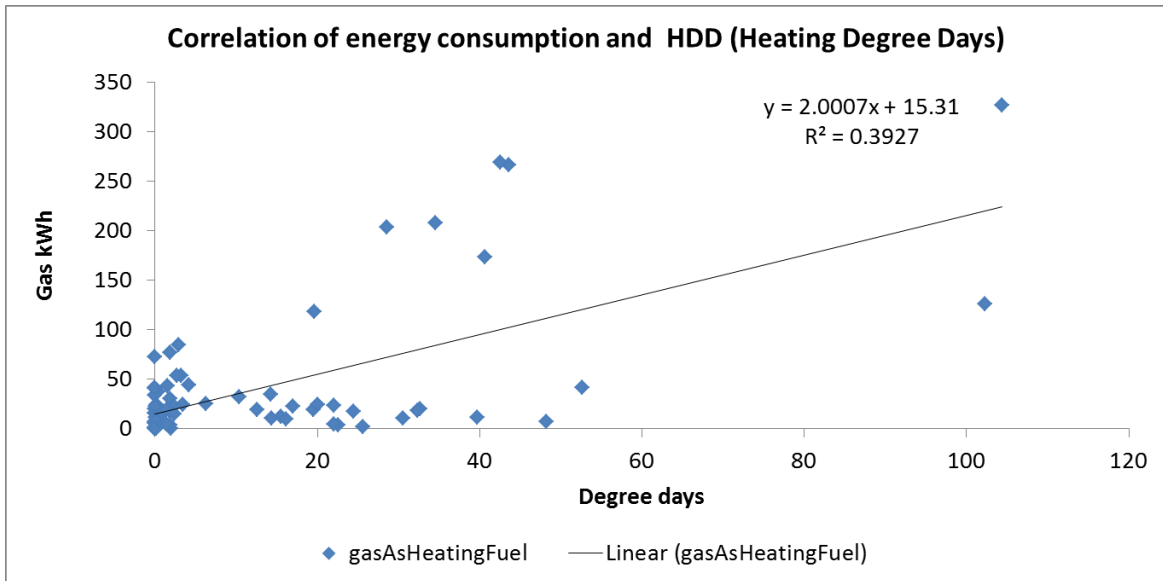
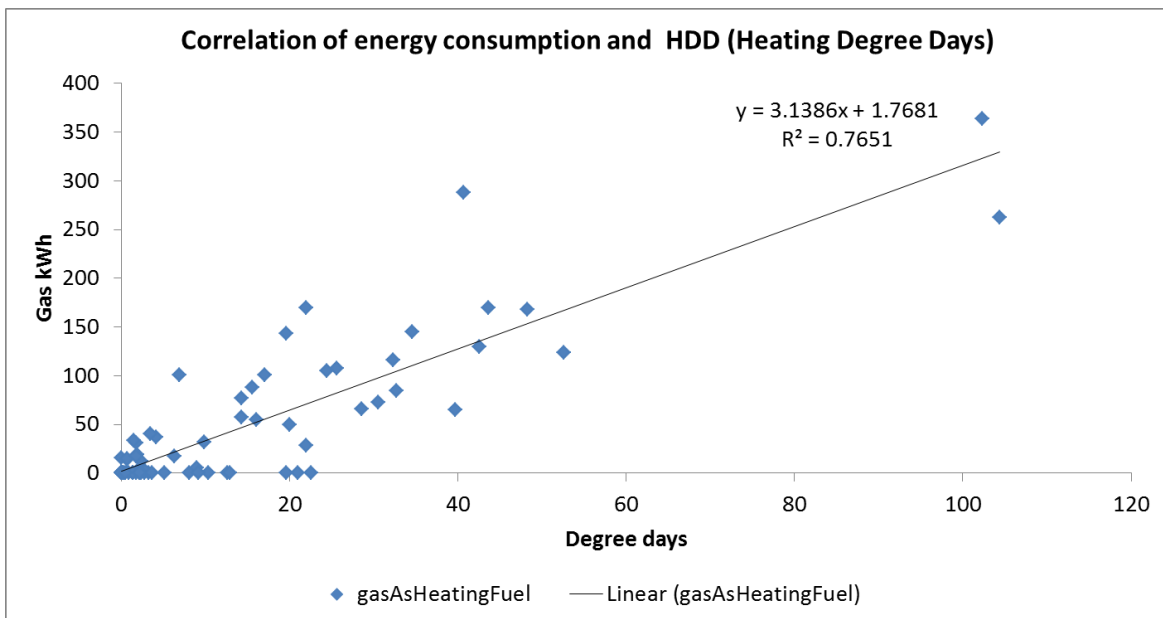
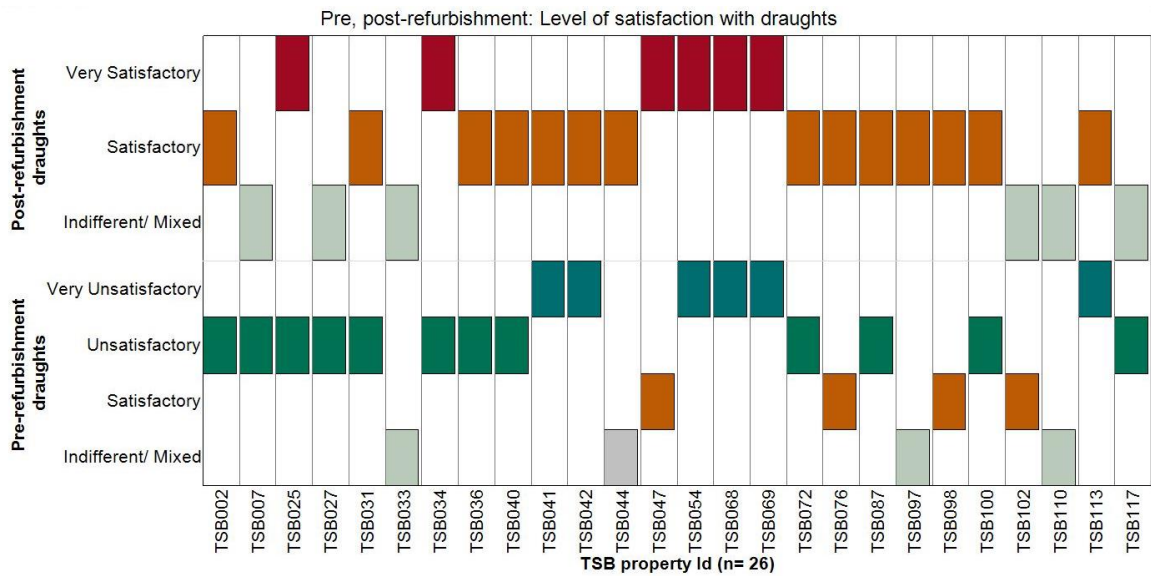
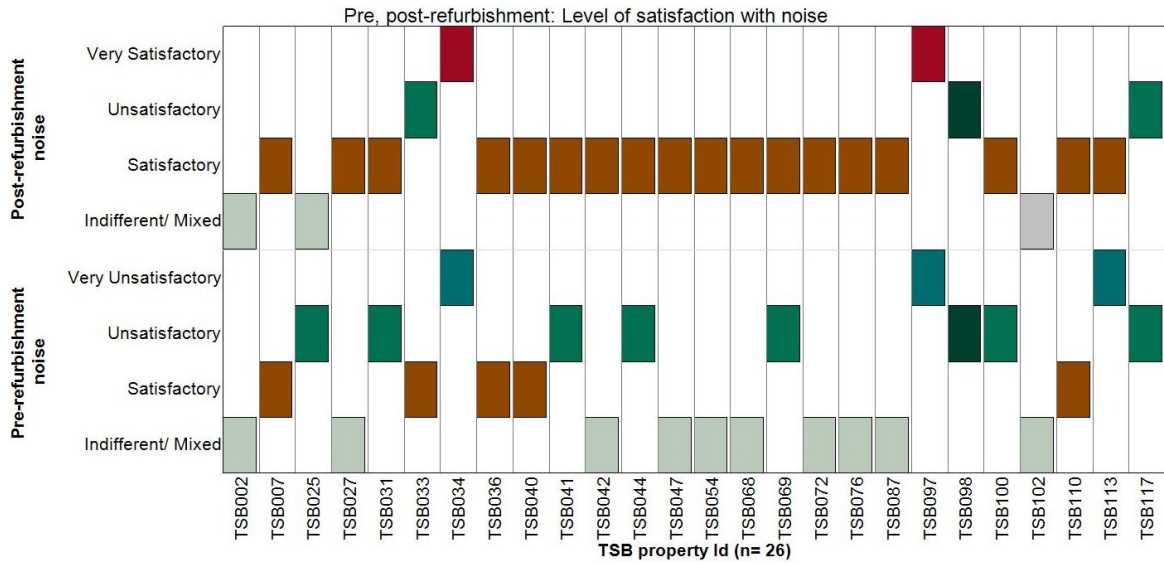


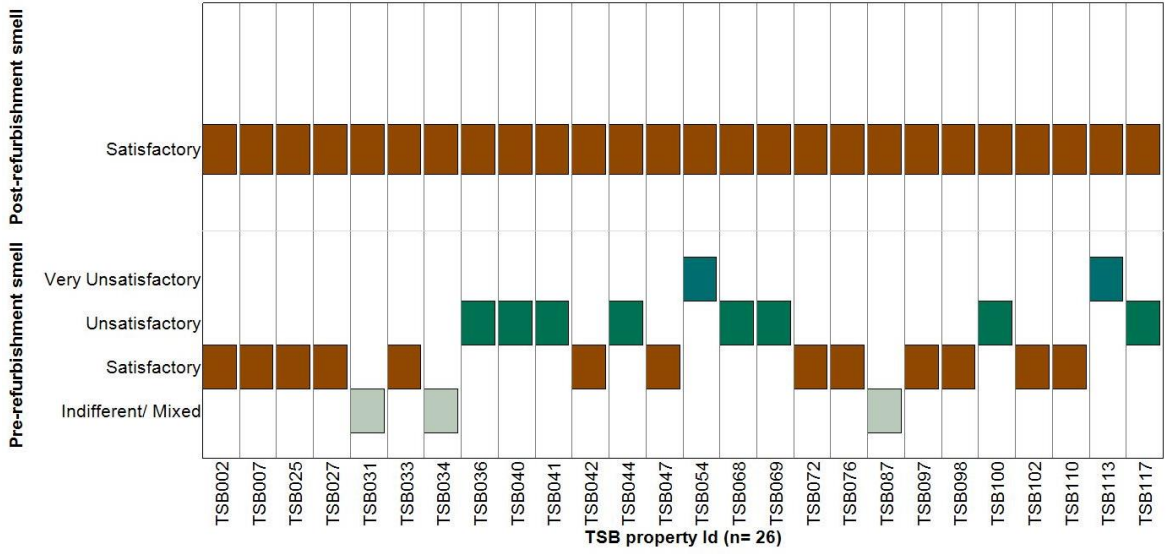
Figure 213: Energy performance line for cases with gas boiler heating system. In TSB072, good correlation of energy consumption and heating degree days was found.



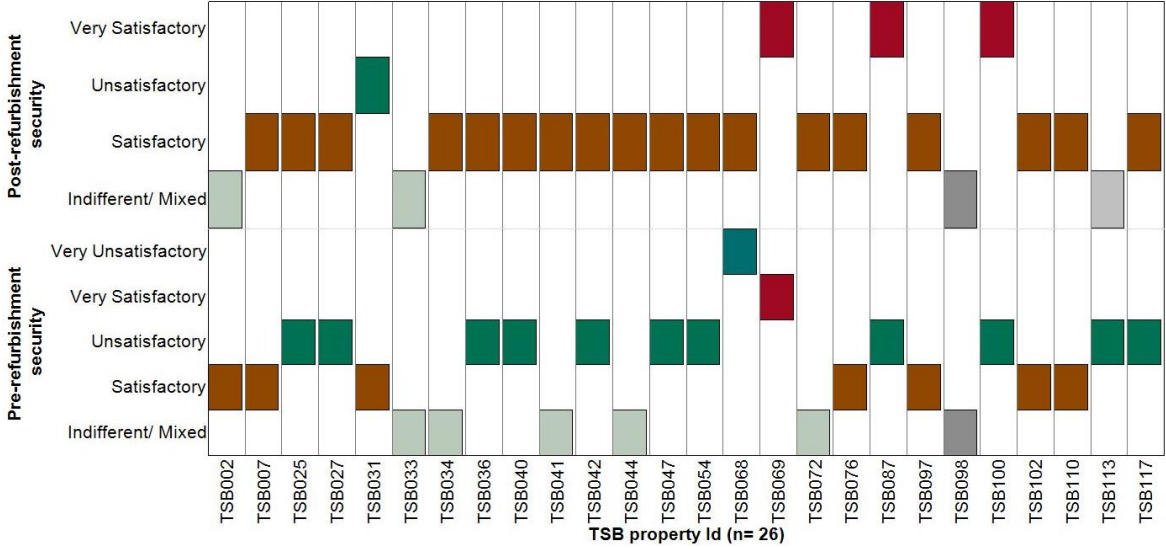
Appendix 25 Figure 214: Pre and post-refurbishment: Occupants' level of satisfaction with factors affecting indoor environment.



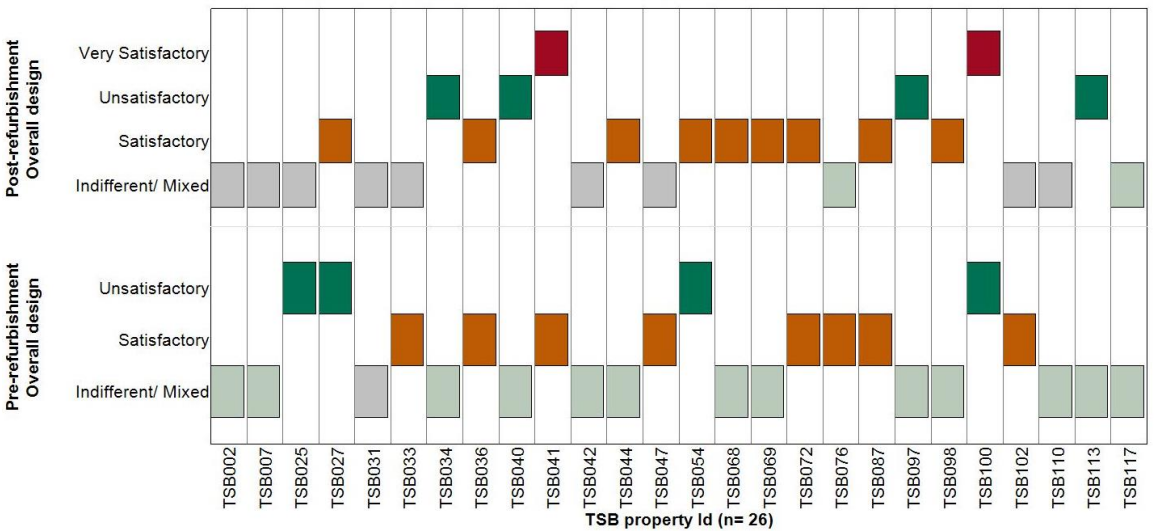
Pre, post-refurbishment: Level of satisfaction with indoor smell

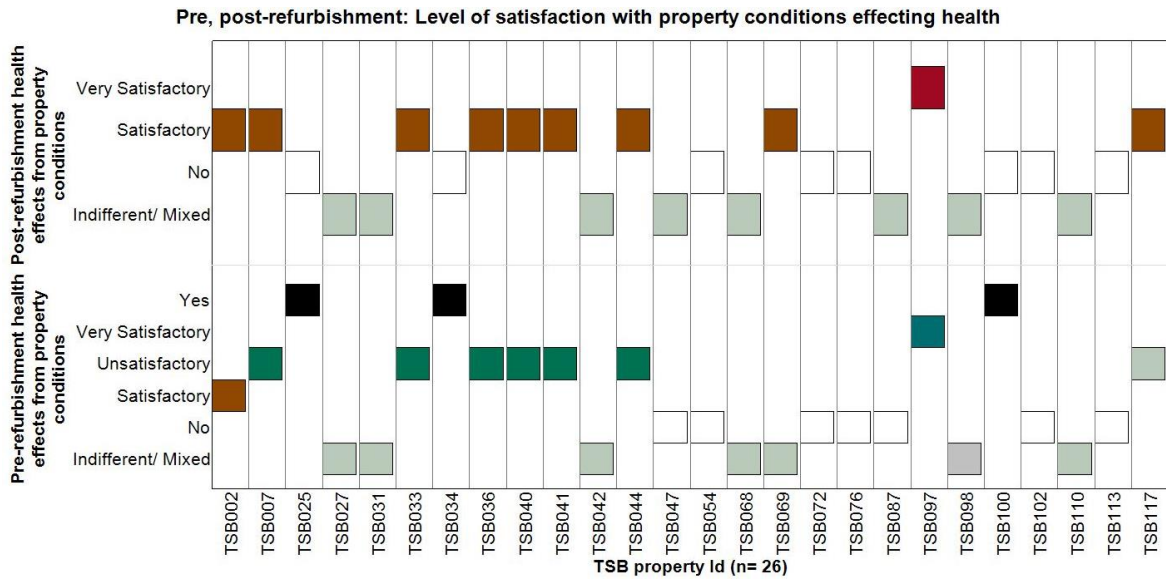


Pre, post-refurbishment: Level of satisfaction with security



Pre, post-refurbishment: Level of satisfaction with overall design





Appendix 26 Table 25: Temperature difference between the Wattbox display and on-site spot check measurements during POE.

<i>TSB id</i>	<i>Collection day</i>	<i>External temp. °C</i>	<i>Wattbox display °C</i>	<i>Mean internal temp. °C</i>	<i>Gr. floor temp. °C</i>	<i>1st floor temp. °C</i>
TSB044	26/01/2012	7	25.3	24.15	22.5	25.8
TSB047	03/02/2012	10	24	20.7	20.0	21.4
TSB041	10/12/2011	2	24.7	20.2	19.4	21.1
TSB040	13/02/2012	2	21.1	19.9	19.7	20.1
TSB042	10/12/2011	2	40	19.5	19.1	19.9
TSB036	11/10/2011	16	23.9	23.6	23.2	24.1
TSB033	26/01/2012	7	5	21.3	20.0	22.7
TSB076	24/11/2011	12	23.7	21.9	21.1	22.7
TSB087	09/03/2012	9	18.4	19.9	19.8	20.1
TSB100	09/03/2012	9	19.2	18.3	18.5	18.0
TSB034	08/09/2011	16	21	19.5	19.0	20.0


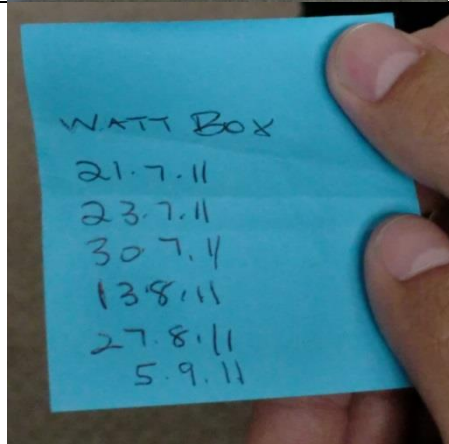


Problems with heating systems	
	<p><i>Figure 215: TSB033, operation problems in one bedroom of the thermo skirting heater control due to installation.</i></p>
	<p><i>Figure 216: TSB034, communication problems between the CHP and Wattbox in heating (water and space heating) until the day of the interview 08/09/2011.</i></p>
Problems in ventilation systems' installation	
Natural ventilation windows	
	<p><i>Figure 217: TSB044, kitchen window above the sink problem in operation due to the height of the handle position and reaching distance from the user.</i></p>
	<p><i>Figure 218: TSB047, kitchen window above the sink problem in operation due to the height of the handle position and reaching distance from the user, as well as window wing cannot be fully opened as blocked by kitchen cupboard.</i></p>



Figure 219: TSB034, kitchen window above the sink problem in operation due to the width of wall insulation, height of the handle position and reaching distance from the user.



Figure 220: TSB110, kitchen window above the sink problem in operation window cannot be fully opened as blocked by the sink tap.



Figure 221: TSB110, problem in operation of the hall way window, as not only window handle cannot be reached by the user but also cannot be opened as blocked by the staircase rail.



Figure 222: TSB 041, draughts from window due installation faults (gap between the window frame and board sill).



Figure 223: TSB042, kitchen window above the sink problem in operation due to the height of the handle position and reaching distance from the user.



Figure 224: TSB069, kitchen window above the sink problem in operation due to increased insulation thickness of the wall and reaching distance for the user.

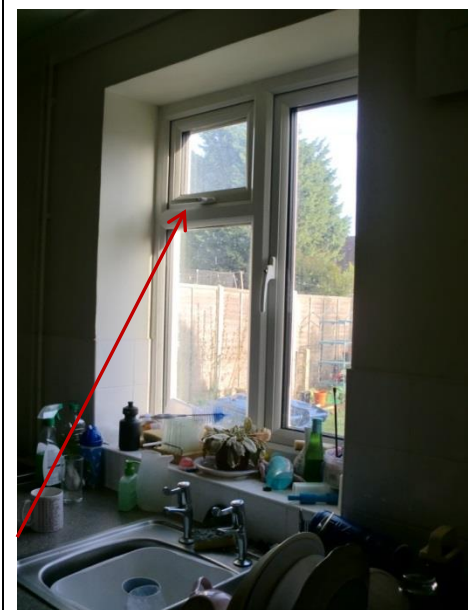


Figure 225: TSB025, kitchen window above the sink problem in operation due to the height of the handle position and reaching distance from the user.



Figure 226: TSB033, kitchen window above the sink problem in operation due to the height of the handle position and reaching distance from the user.



Figure 227: TSB076, kitchen window above the sink problem in operation to be fully opened due to the handle's reaching distance from the user.

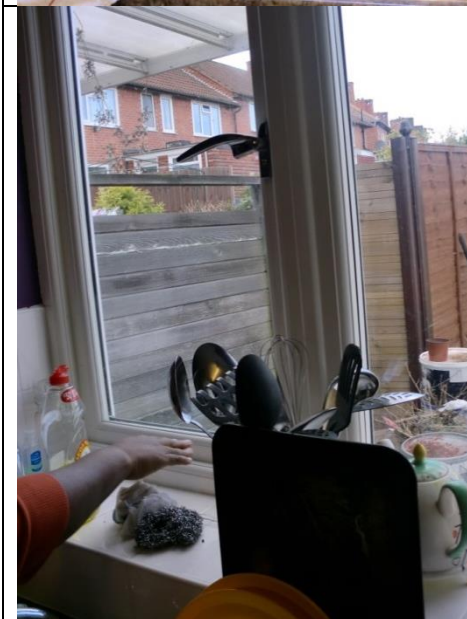


Figure 228: TSB117, kitchen window above the sink problem in operation due to the height of the handle position and reaching distance from the user.

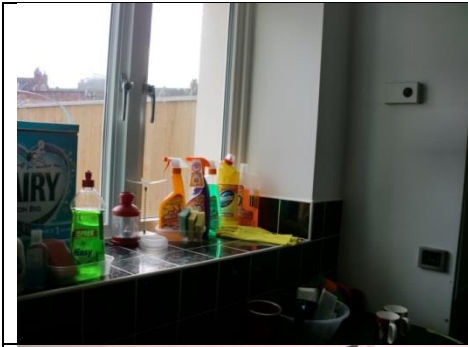


Figure 229: TSB098, kitchen window above the sink problem in operation due to the height of the handle position and reaching distance from the user.

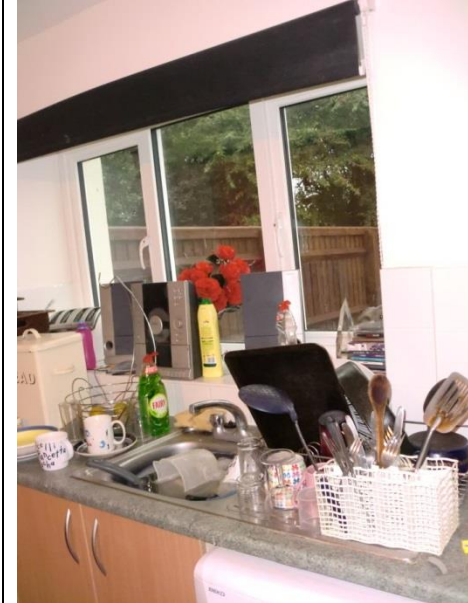


Figure 230: TSB113, kitchen window above the sink problem in operation due to the height of the handle position and reaching distance from the user.



Figure 231: TSB036, operational problems in window opening due to increased size of bedroom window occupying large area of living space.



Figure 232: TSB054, operational problems in window opening due to one pane triple glazed window, pivot/tilt opening type increasing window weight and security issues due to lowering the window's sill plate.

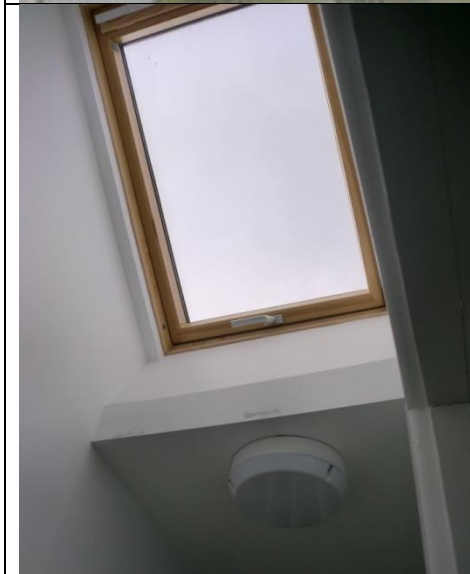










Figure 233: TSB098, operational problems in window opening, difficulty to operate it with the telescopic pole due to the height and weight.



Figure 234: TSB042, gap doors' undercut in this case the gap is bigger than designed resulting to significant heat losses in the living room from the unheated entrance hall and stair space.

	<p><i>Figure 235: TSB102, draughts from the front door due to fitting problems of the door and incomplete floor finish works.</i></p>
	<p><i>Figure 236: TSB027, draughts from the back door due to installation faults.</i></p>
	<p><i>Figure 237: TSB036, operational problems in opening bedroom door due to wrong location of the light fitting.</i></p>
	<p><i>Figure 238: TSB036, operational problems in door window opening due to increased size and opening inwards instead of outwards occupying large area of living space.</i></p>

Problems with ventilation systems	
	<p><i>Figure 239: TSB076, operational problem MEV fan in joined switcher with the light does not allow users to take the steam out with our having the light ON.</i></p>
	<p><i>Figure 240: TSB025, operational problem in and reaching MVHR boost button.</i></p>
	<p><i>Figure 241: TSB097, operational problem in and reaching MVHR control button.</i></p>
	<p><i>Figure 242: TSB117, operational problem in and reaching MEV fan button.</i></p>
	<p><i>Figure 243: TSB027, operational problem in and reaching MEV fan button.</i></p>

	<p><i>Figure 244: TSB076, operational problem of the MEV fan due to location inside the bathroom cupboard unable to extract all the steam out.</i></p>
	<p><i>Figure 245: TSB044 cooking extractor fan installed to recirculate air inside instead of as releasing it through outside vent extracting moisture and odours outside.</i></p>
<p>Other design issues identified</p>	
	<p><i>Figure 246: TSB102, occupants' alteration on the projects' design fault in order to have access and operate the washing machine.</i></p>

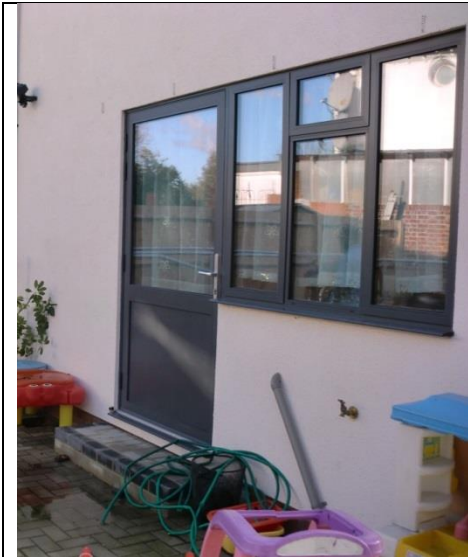


Figure 247: TSB033, although the door window size was designed for wheelchair access a door step prevents the access.



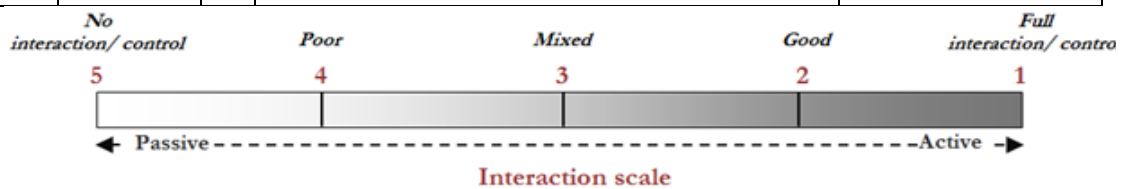
Figure 248: TSB113, cracks on the ceiling.

Appendix 28 Table 26: Controls of systems and measures ‘as designed’/installed and occupants’ level of interaction (n=26).

Systems and measures in use

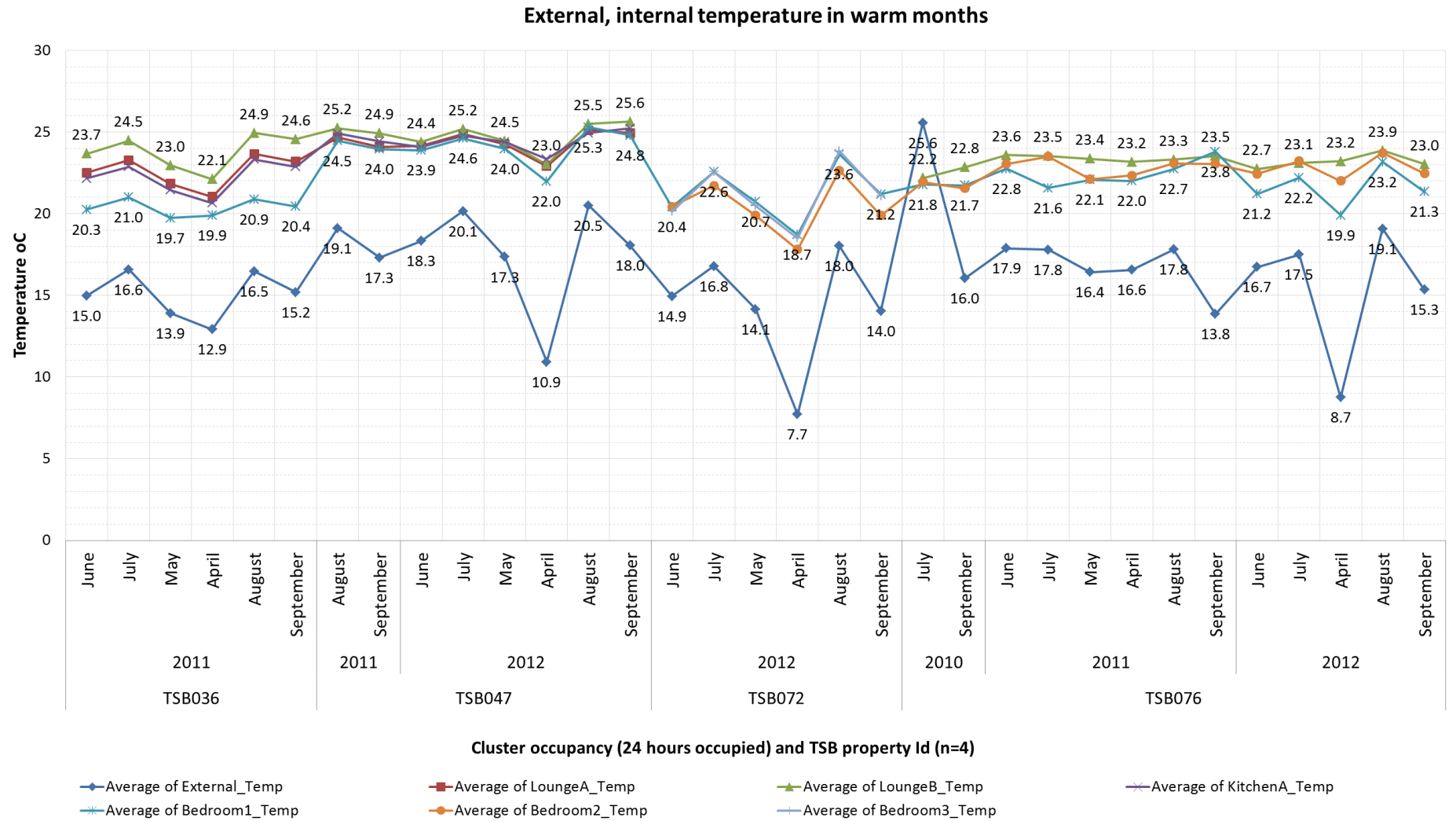
<i>Direct or indirect system operation</i>		<i>Via measures</i>	<i>Controls installed for passive or active (in n cases in the sample)</i>	<i>Levels of interaction with the measure (in n cases in the sample)</i>	
Heating					
Space	Gas Boiler	Direct	Gas boiler controls	<i>Active users: n=8</i> <i>Passive users: n=1</i>	<i>n=3 Level 3</i> <i>n=6 Levels 4 and 5</i>
			CHP boiler controls	<i>Pass users n=7</i>	<i>n=7 Levels 4 and 5</i>
			Heat pump boiler controls	<i>Passive users n=6</i>	<i>n=1 Level 3</i> <i>n=5 Levels 4 and 5</i>
			Biomass boiler	<i>Passive users n=4</i>	<i>n=4 Levels 4 and 5</i>
	micro-CHP	Indirect	Programmer	<i>Active users n=11</i>	<i>n=6 Levels 1 and 2</i> <i>n=4 Level 3</i> <i>n=1 Levels 4 and 5</i>
	Heat pumps		Thermostat	<i>Active users n=10</i>	<i>n=7 Levels 1 and 2</i> <i>n=2 Level 3</i> <i>n=1 Levels 4 and 5</i>
	Biomass		Intelligent control systems (Wattbox, Optima Design Controller)	<i>Active users n=13</i>	<i>n=2 Levels 1 and 2</i> <i>n=10 Level 3</i> <i>n=1 Levels 4 and 5</i>
			TRVs	<i>Active users n=21</i>	<i>n=11 levels 1 and 2</i> <i>n=3 Level 3</i>
			Storage heater controls	<i>Active users n=2</i>	<i>n=9 Levels 4 and 5</i>
	Hot water		Gas boiler	Direct	Gas boiler controls
CHP boiler controls		<i>Passive users n=4</i>			<i>n=4 Levels 4 and 5</i>
Heat pump boiler controls		<i>Passive users n=6</i>			<i>n=1 Level 3</i> <i>n=5 Levels 4 and 5</i>
Biomass boiler		<i>Passive users n=4</i>			<i>n=4 Levels 4 and 5</i>
Solar thermal controls		<i>Passive users: n=2</i>			<i>n=2 Levels 4 and 5</i>
Biomass		Indirect	Programmer	<i>Active users n=11</i>	<i>n=5 Levels 1 and 2</i> <i>n=2 Level 3</i> <i>n=4 Levels 4 and 5</i>
Solar					

Ventilation					
<i>Natural</i>	Windows	<i>Direct</i>	Window operation	<i>Active users n=12</i> <i>Active/Passive users n=14</i>	<i>n=8 Levels 1 and 2</i> <i>n=14 Level 3</i> <i>n=4 Levels 4 and 5</i>
			Door operation	<i>Active users n=26</i>	<i>n=17 Levels 1 and 2</i> <i>n=5 Level 3</i> <i>n=4 Levels 4 and 5</i>
	Doors	<i>Indirect</i>	Windows' trickle vents	<i>Active users n=8</i>	<i>n=8 Levels 4 and 5</i>
			Doors' undercut gap	<i>Passive users n=3</i>	<i>n=3 Levels 4 and 5</i>
<i>Mechanical</i>	MVHR	<i>Direct</i>	MVHR unit controls	<i>Passive users n=4</i>	<i>n=4 Levels 4 and 5</i>
			MEV fans ON/OFF	<i>Active users n=1</i> <i>Active/Passive users n=5</i>	<i>n=1 Levels 1 and 2</i> <i>n=5 Levels 4 and 5</i>
	MEV fans	<i>Indirect</i>	Control panel	<i>Active users n=8</i>	<i>n=2 Levels 1 and 2</i> <i>n=6 Levels 4 and 5</i>
			Boost button	<i>Active users n=11</i>	<i>n=5 Levels 1 and 2</i> <i>n=2 Level 3</i> <i>n=4 Levels 4 and 5</i>
			Air valve controls	<i>Active users n=12</i>	<i>n=3 Levels 1 and 2</i> <i>n=1 Level 3</i> <i>n=8 Levels 4 and 5</i>



Interaction Levels: 1(Full interaction/control) and 2(Good), Level 3(Mixed interaction), Levels 4(Poor) and 5(No interaction/control)

Appendix 29 Figure 249: Cluster occupancy-24 hours occupied: Internal and external temperatures and 24 hours occupancy in warm months.



Appendix 30 Figure 250: Cluster occupancy - 24 hours occupied: Internal and external temperatures and 24 hours occupancy in cold months.

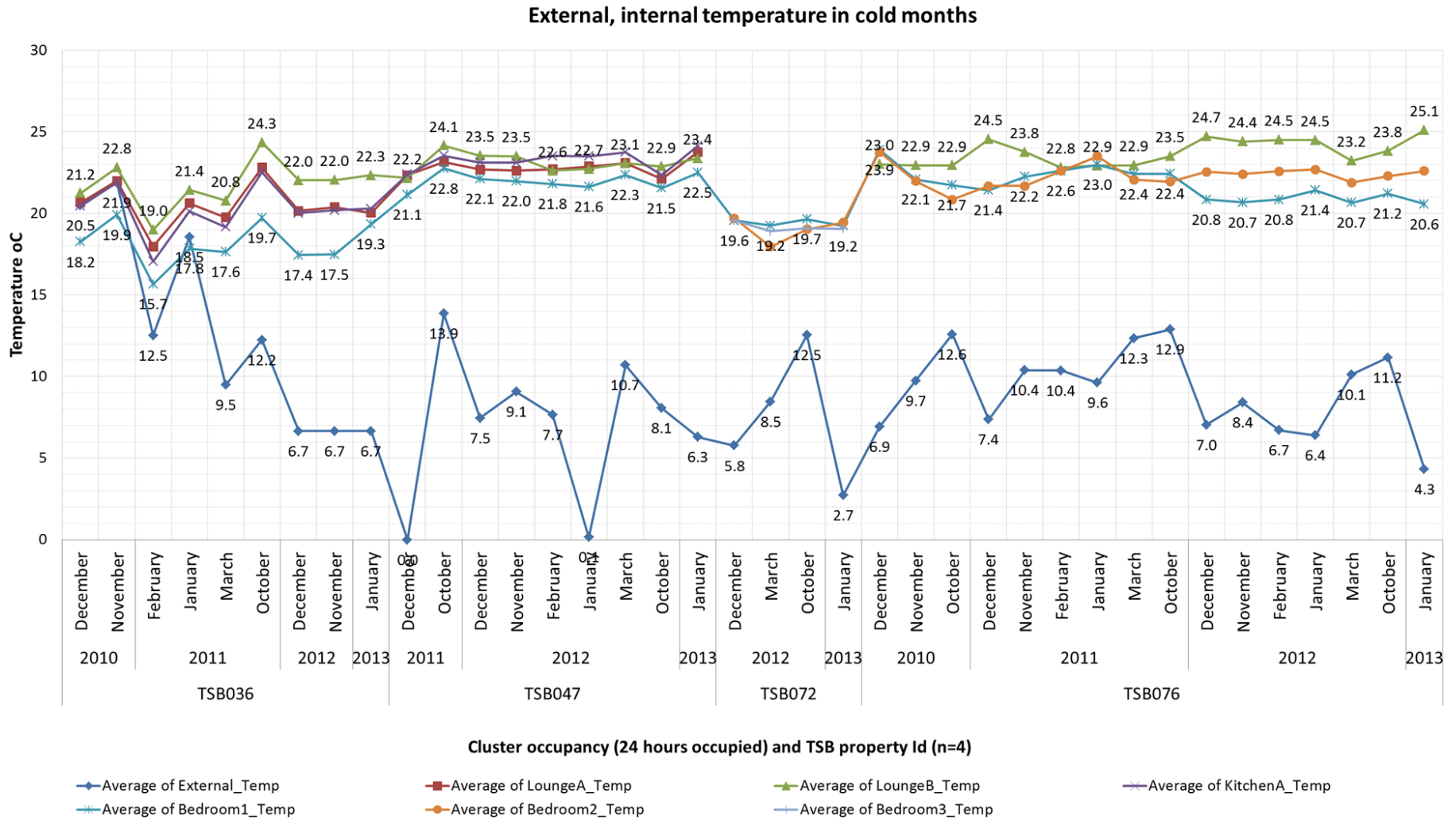


Figure 251: Cluster occupancy 22 - 24 hours occupied: Internal and external temperatures and 22-24 hours occupancy in cold months.

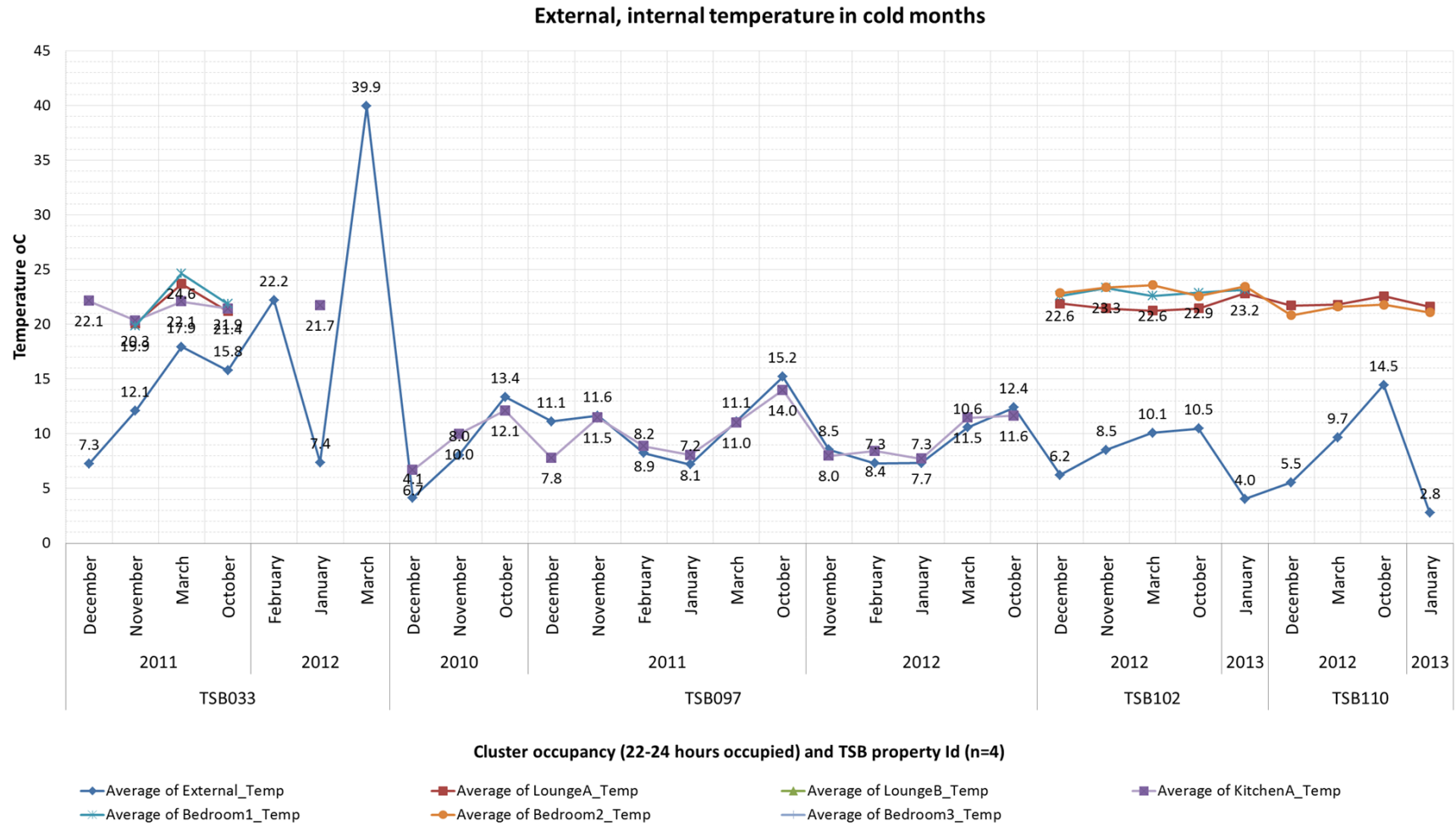
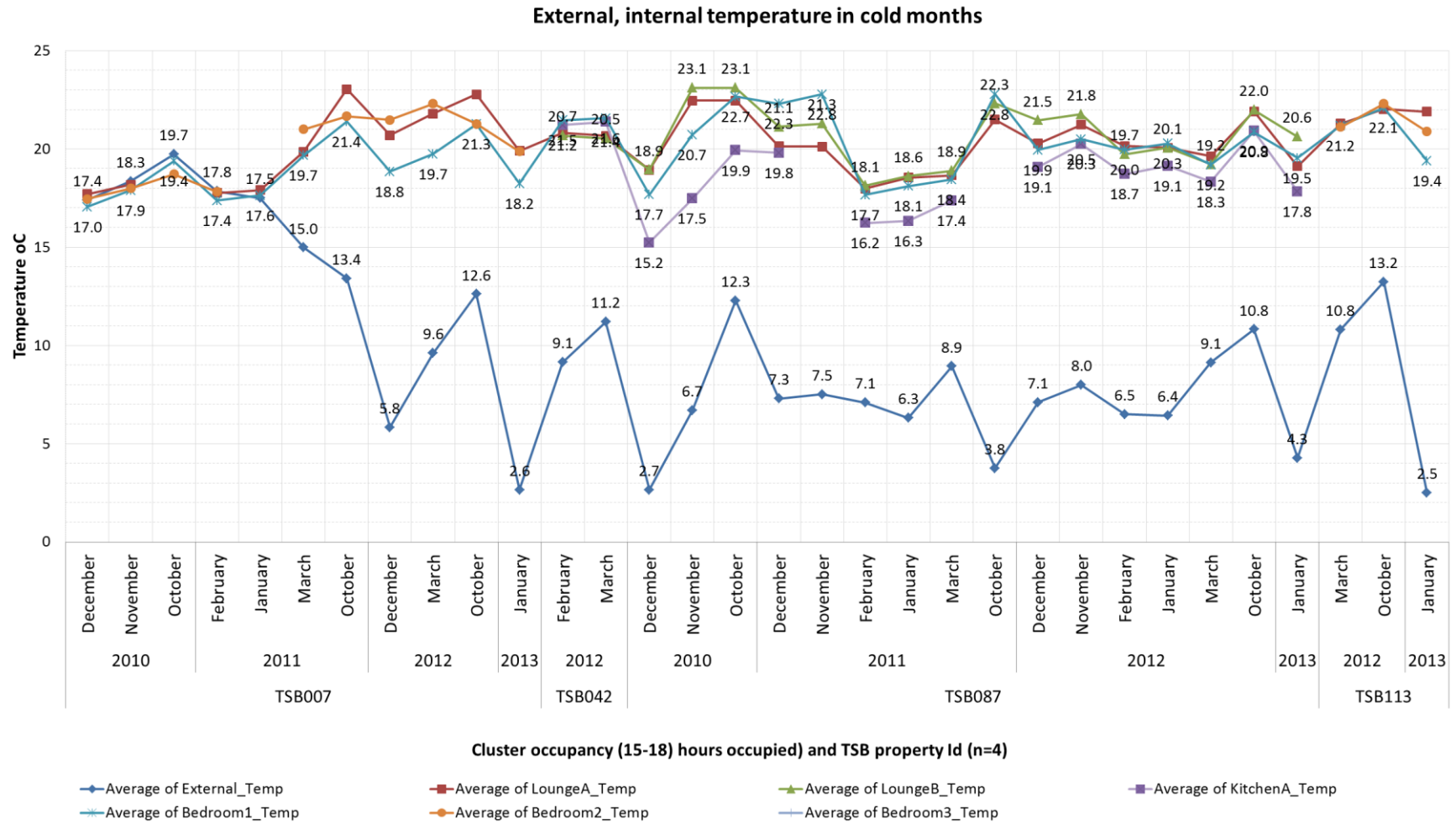
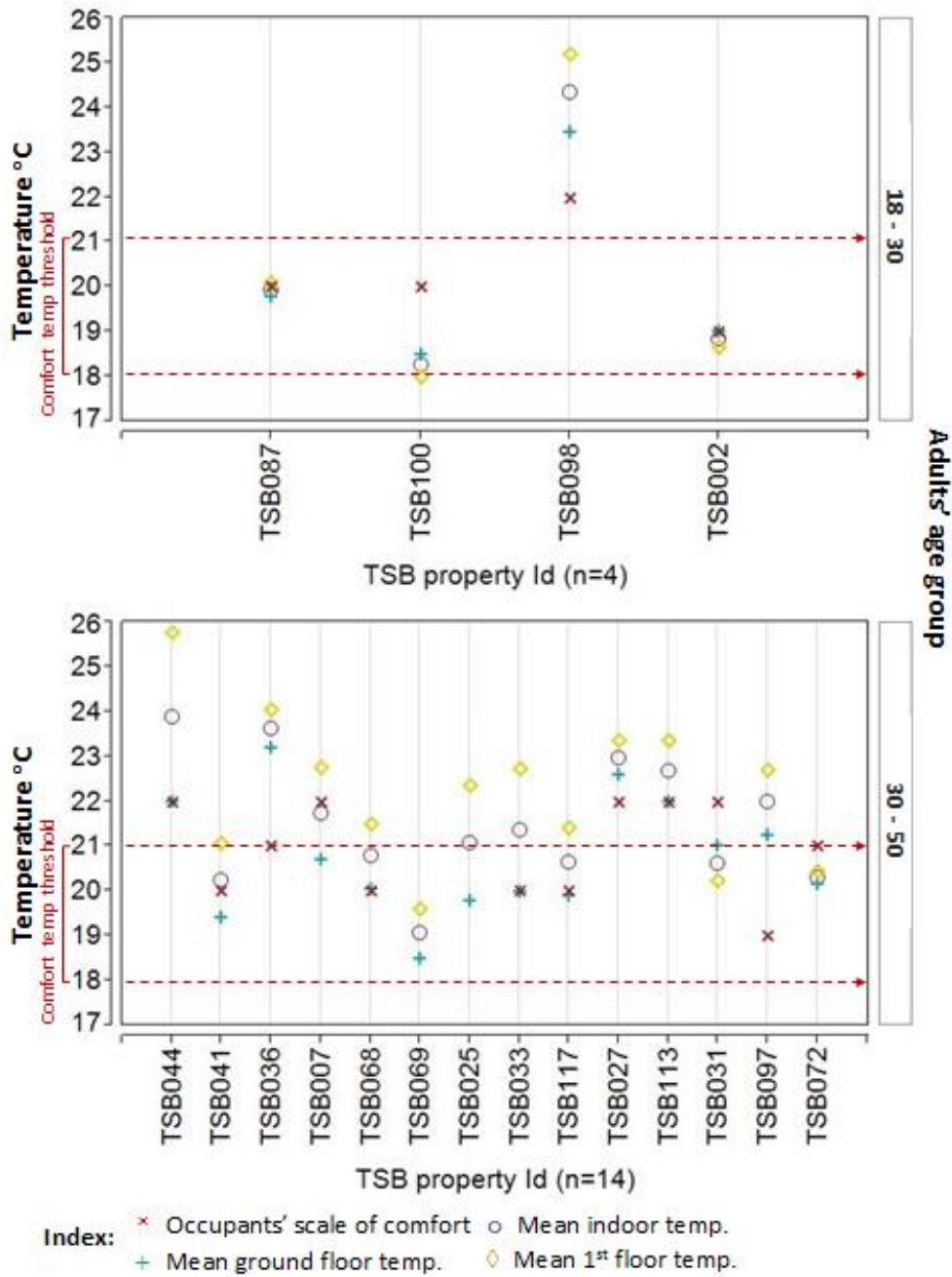
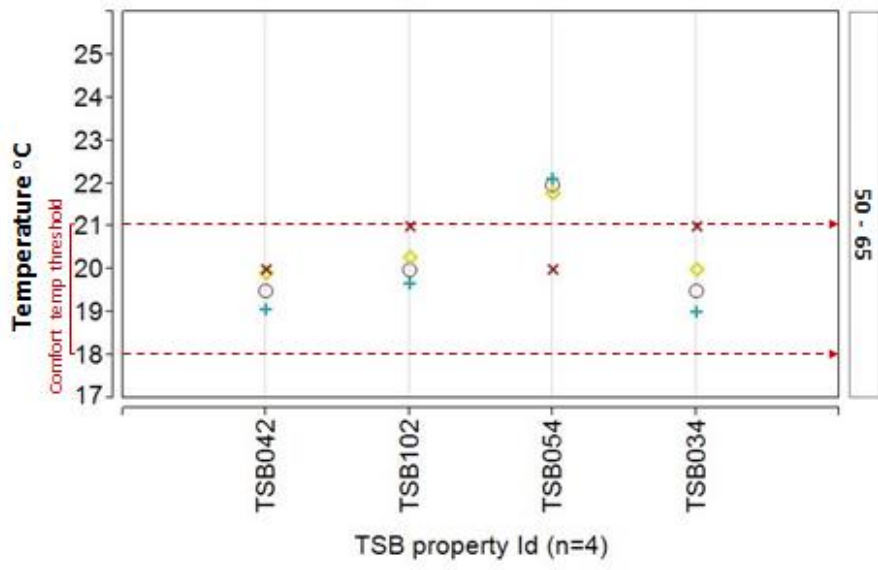


Figure 252: Cluster occupancy - 24 hours occupied: Internal and external temperatures and 24 hours occupancy in cold months.

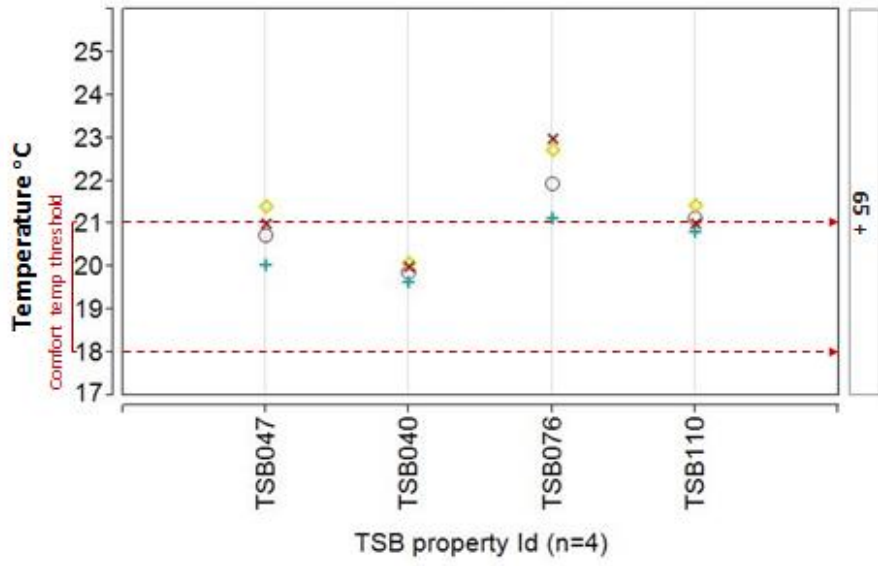


Appendix 31 Figure 253: Occupants' comfort sensation, indoor mean temperatures and age group.



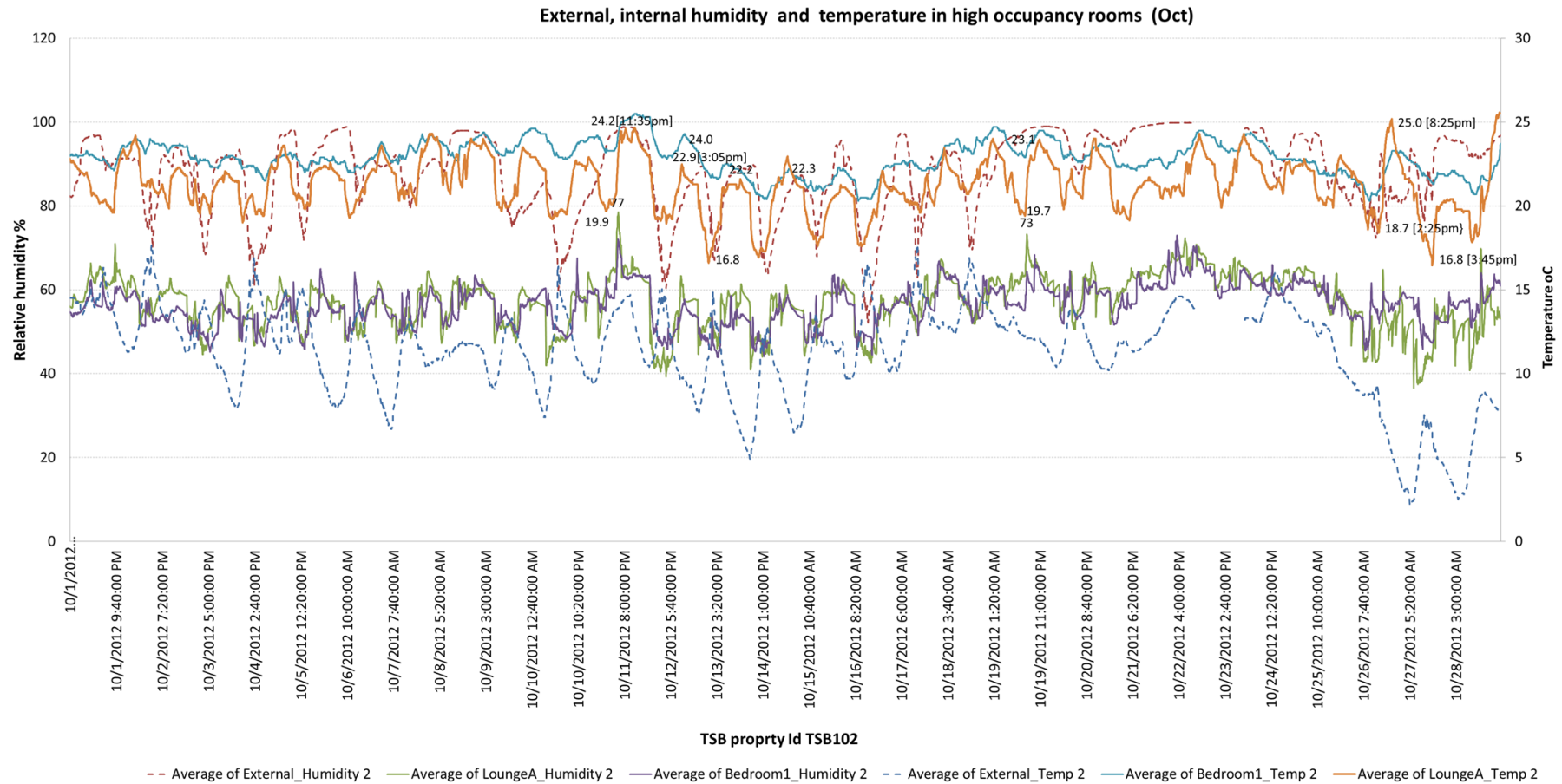


Adults' age group

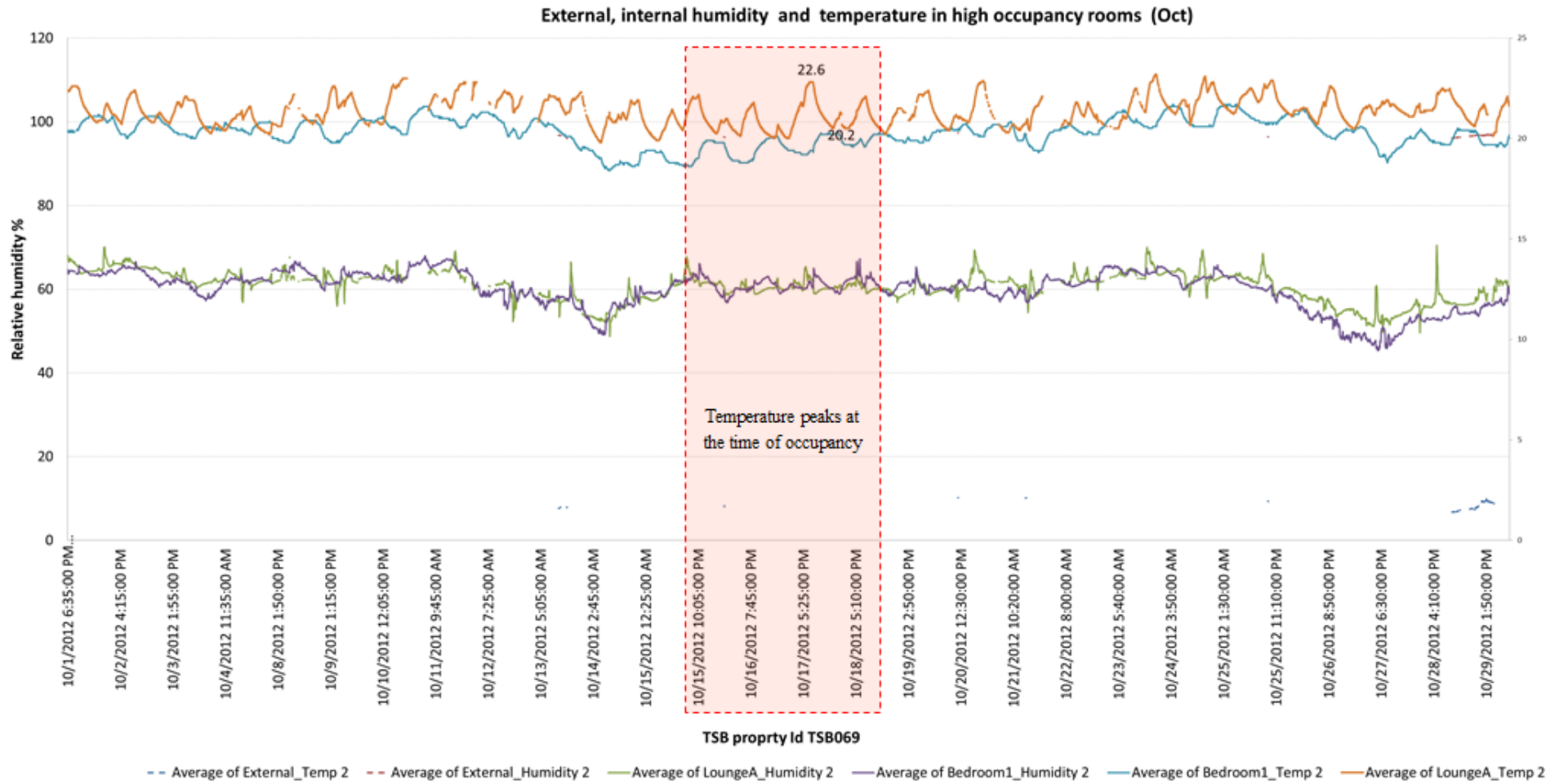


Index: x Occupants' scale of comfort diamond Mean indoor temp.
 + Mean ground floor temp. diamond Mean 1st floor temp.

Appendix 32 Figure 254: Cross-checking occupants' doings and sayings. The peaks and drops of temperature and humidity indicate the lack of heating controls, the use of secondary heaters and some of windows opening all the time throughout the day as reported from the occupants.



Appendix 33 Figure 255: Convective heating systems' control (programmer) and temperature variation. Case TSB069 occupied 12-15 hours, heating control via programmer set up (temperature peaks at the time of occupancy), occupants open some windows once a day despite the MVHR system that is on 24/7.



Appendix 34 Figure 256 : Intelligent heating systems' control (Wattbox) and temperature variation. Case TSB040 occupied 12-15 hours, smoking habits outdoors, although occupants sayings are having the windows closed humidity values indicate window opening in both living and night zone.

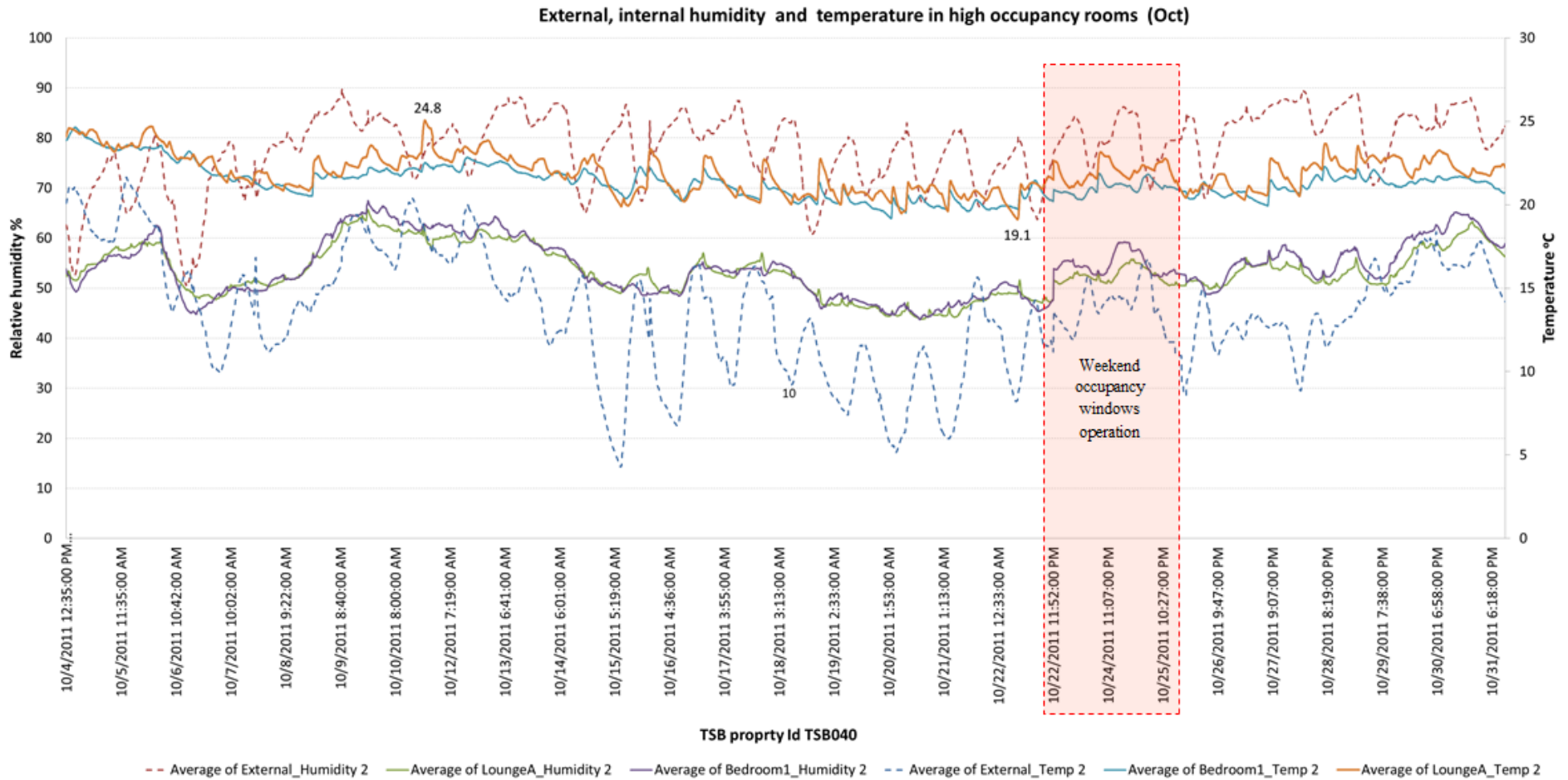


Figure 257: Intelligent heating systems' control (Wattbox) and temperature variation. Case TSB034 occupied 12-15 hours, smoking habits outdoors, although occupants sayings are having the windows always closed humidity values indicate window opening in night zone (main bedroom).

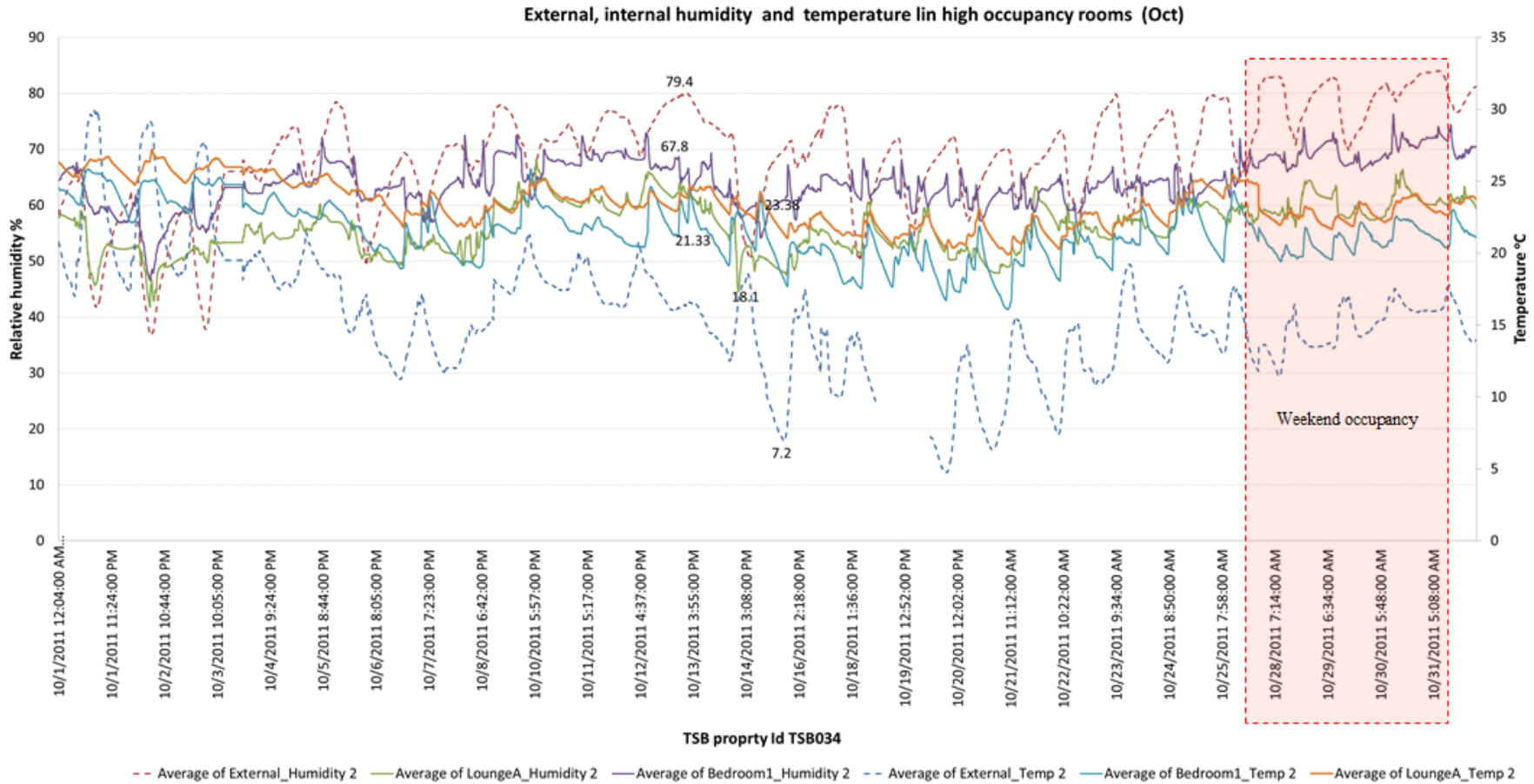


Figure 258: Intelligent heating systems' control (Wattbox) and temperature variation. Case TSB041 occupied 12-15 hours, smoking habits outdoors, although occupants report having the windows always closed there are humidity peaks indicating windows opening especially in night zone (main bedroom).

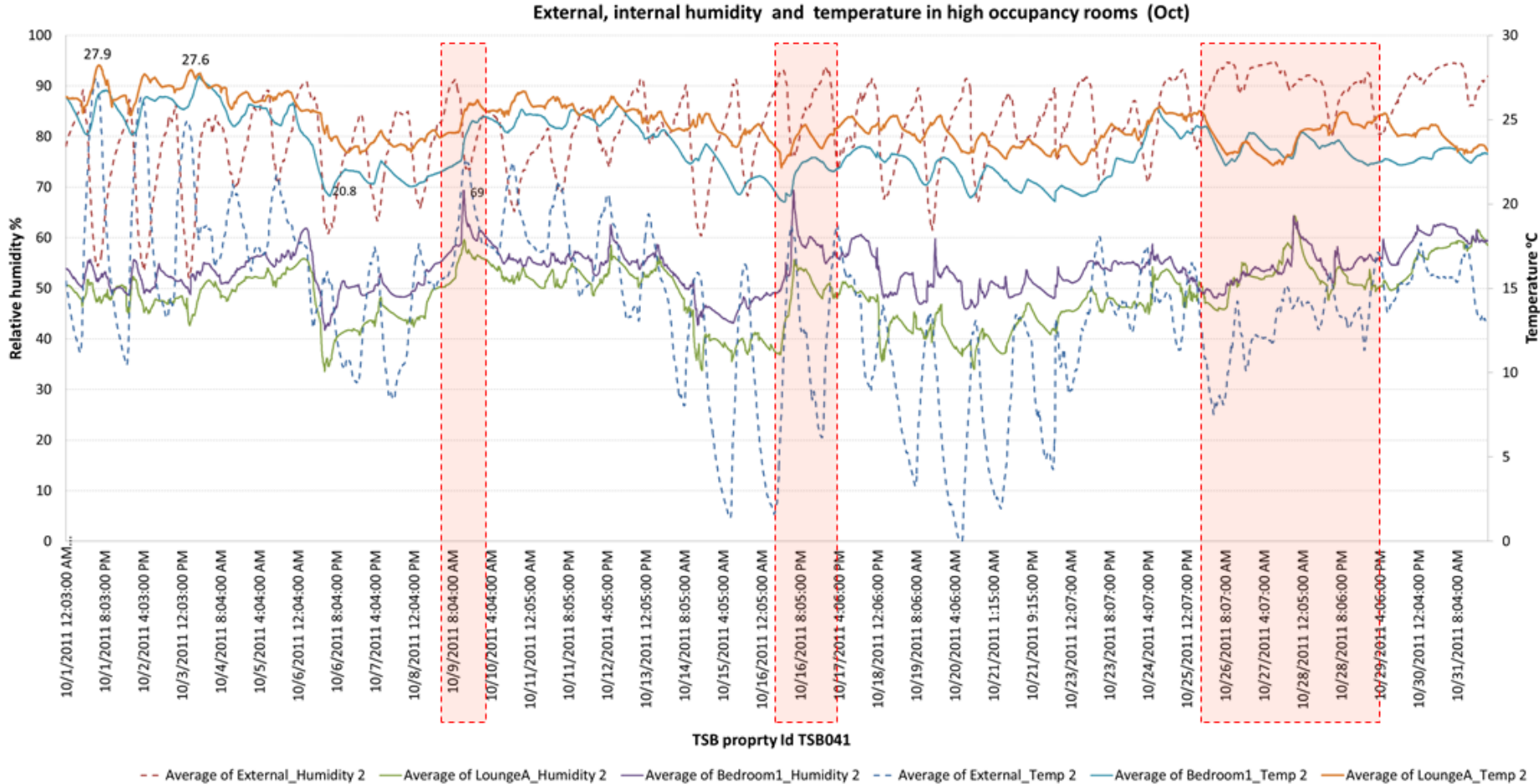


Figure 259: MVHR relative humidity and CO₂ variation. Case TSB041 occupied 12-15 hours, smoking habits outdoors, although occupants report having the windows always closed there are humidity peaks and CO₂ indicating windows opening in cold months.

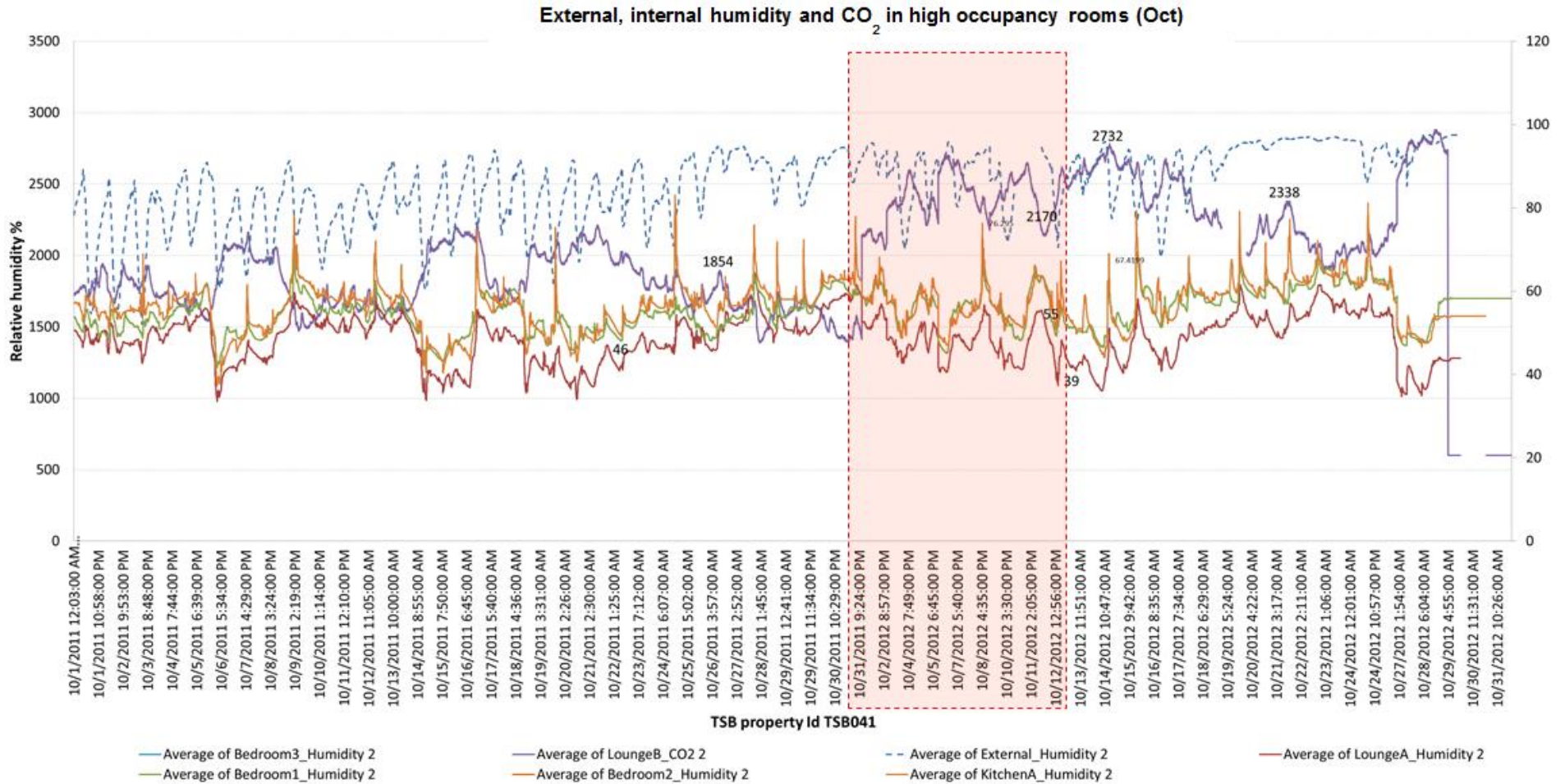


Figure 260: MVHR relative humidity and CO₂ variation. Case TSB041 occupied 12-15 hours, smoking habits outdoors, although occupants report having the windows always closed there are humidity peaks and CO₂ indicating windows opening in warm months.

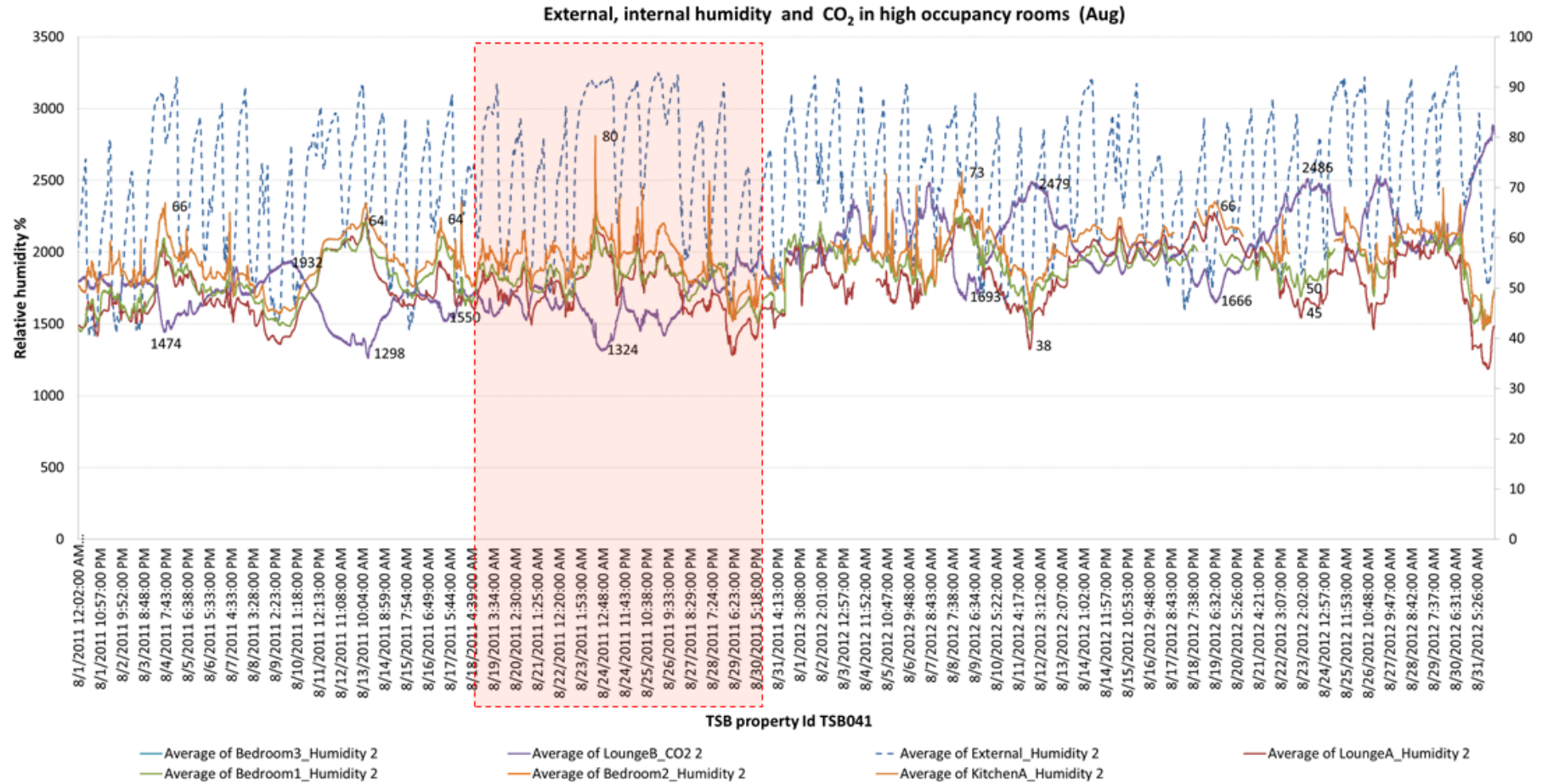


Figure 261: Intelligent heating systems' control (Wattbox) and temperature variation. Case TSB047 occupied 24 hours; windows operation confirms occupants' sayings for occasional opening once a day.

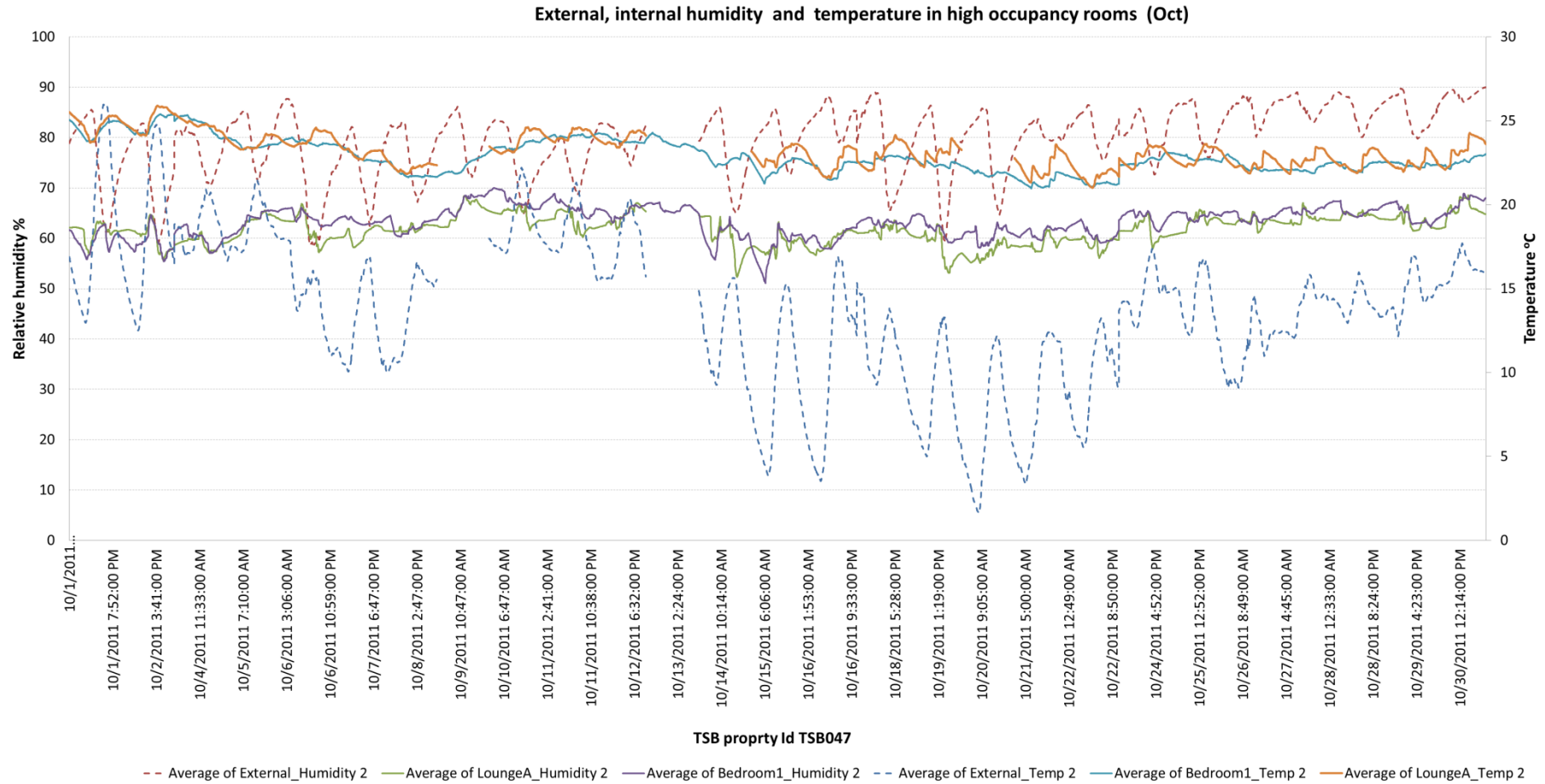


Figure 262: Intelligent heating systems' control (Optima design controller) and temperature variation. Case TSB007 occupied 12-15 hours, open some windows all the time especially in night zone (main bedroom).

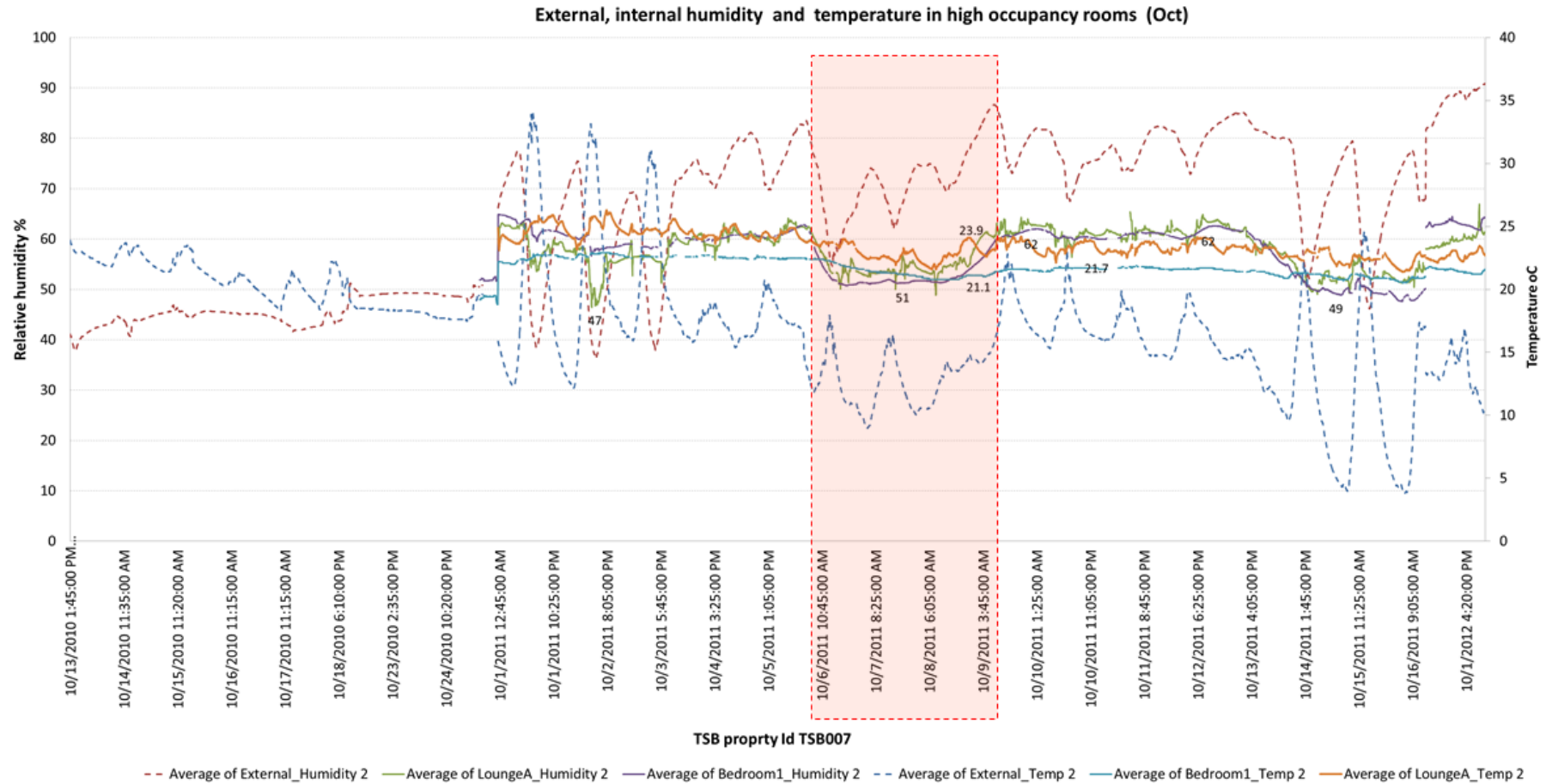
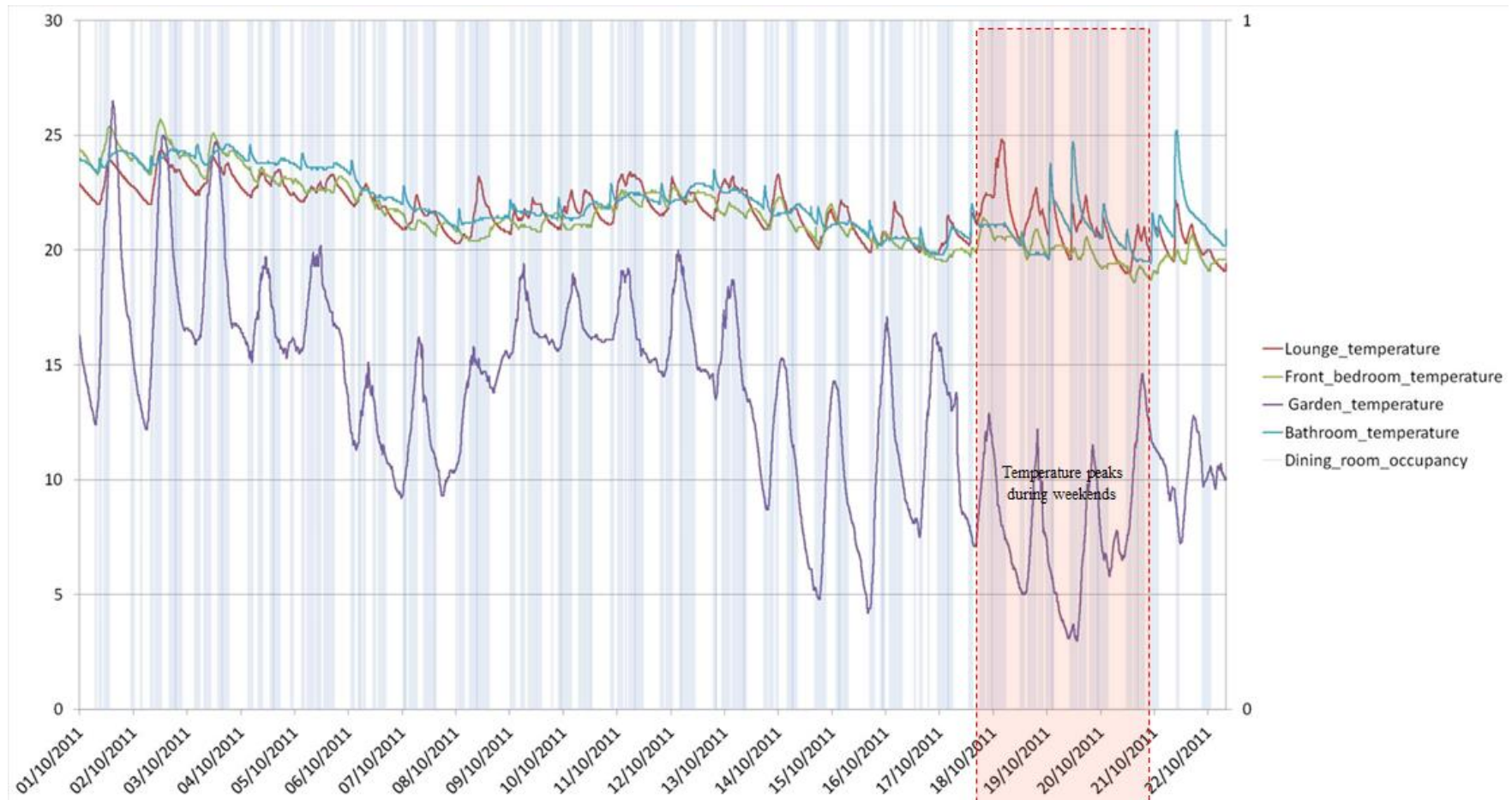


Figure 263: Convective heating systems' control (programmer) and temperature variation. Case TSB054 occupied 24 hours, heating control via programmer set up and thermostat (temperature peaks in the weekends, occasionally with extra visitors), some of the windows are opened all day despite the MVHR system that is on 24/7.



Appendix 35 Figure 264: Window control practices in warm months (Aug). Case TSB110 temperature drops and humidity increase indicate windows opening in addition to the MVHR system operation.

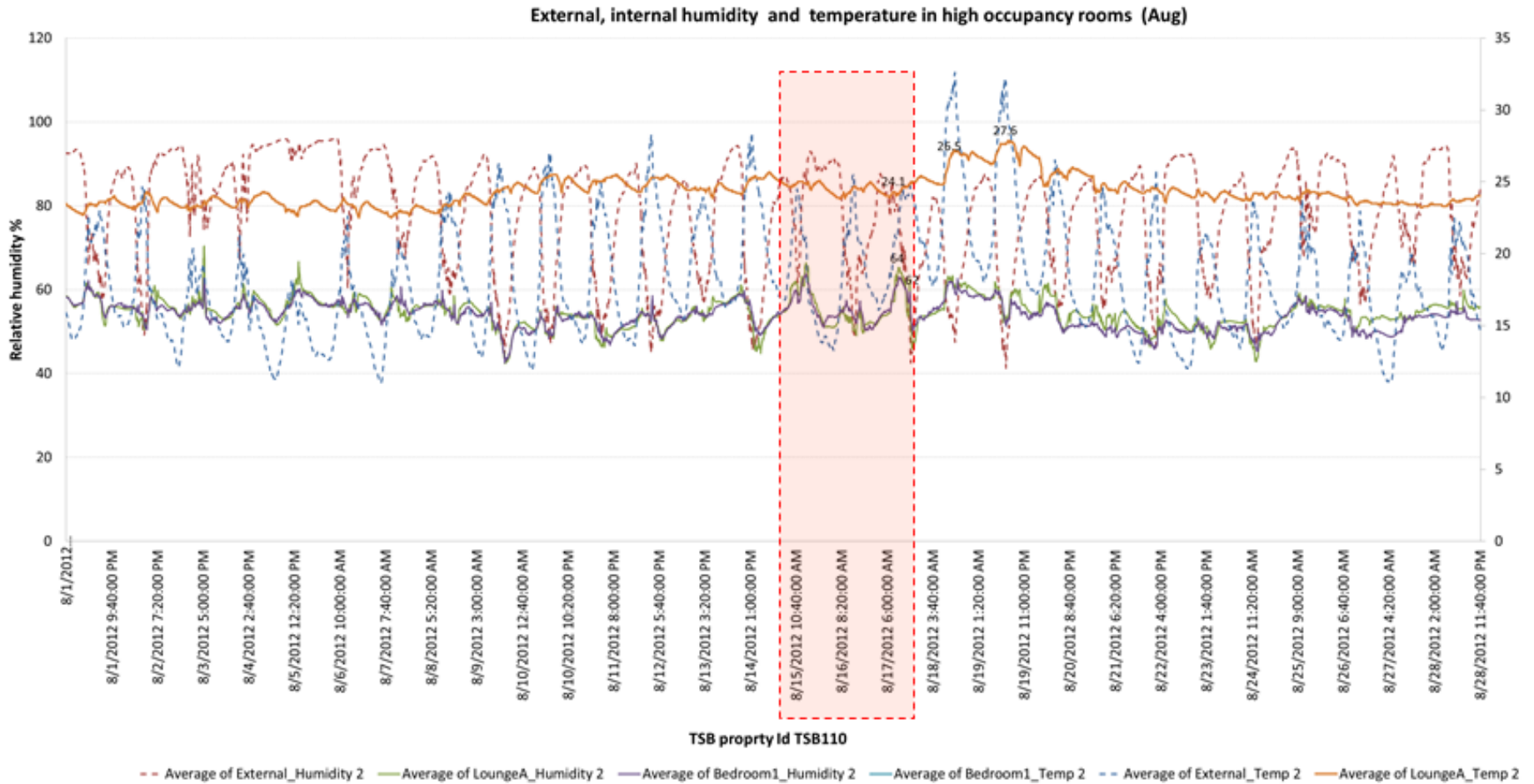


Figure 265: Window control practices in warm months (Aug). Case TSB110 temperature drops and humidity increase indicate windows opening in addition to the MVHR system operation.

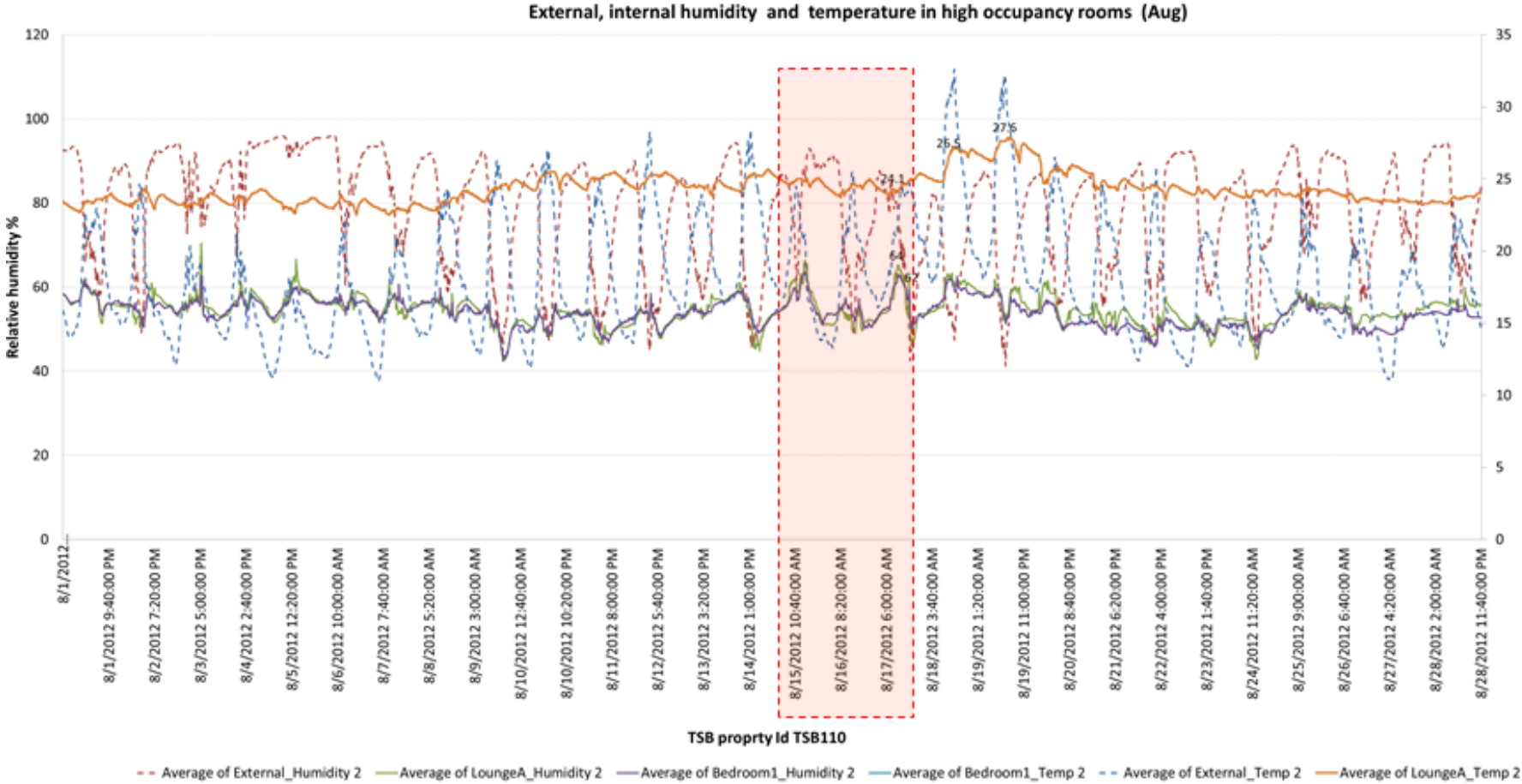
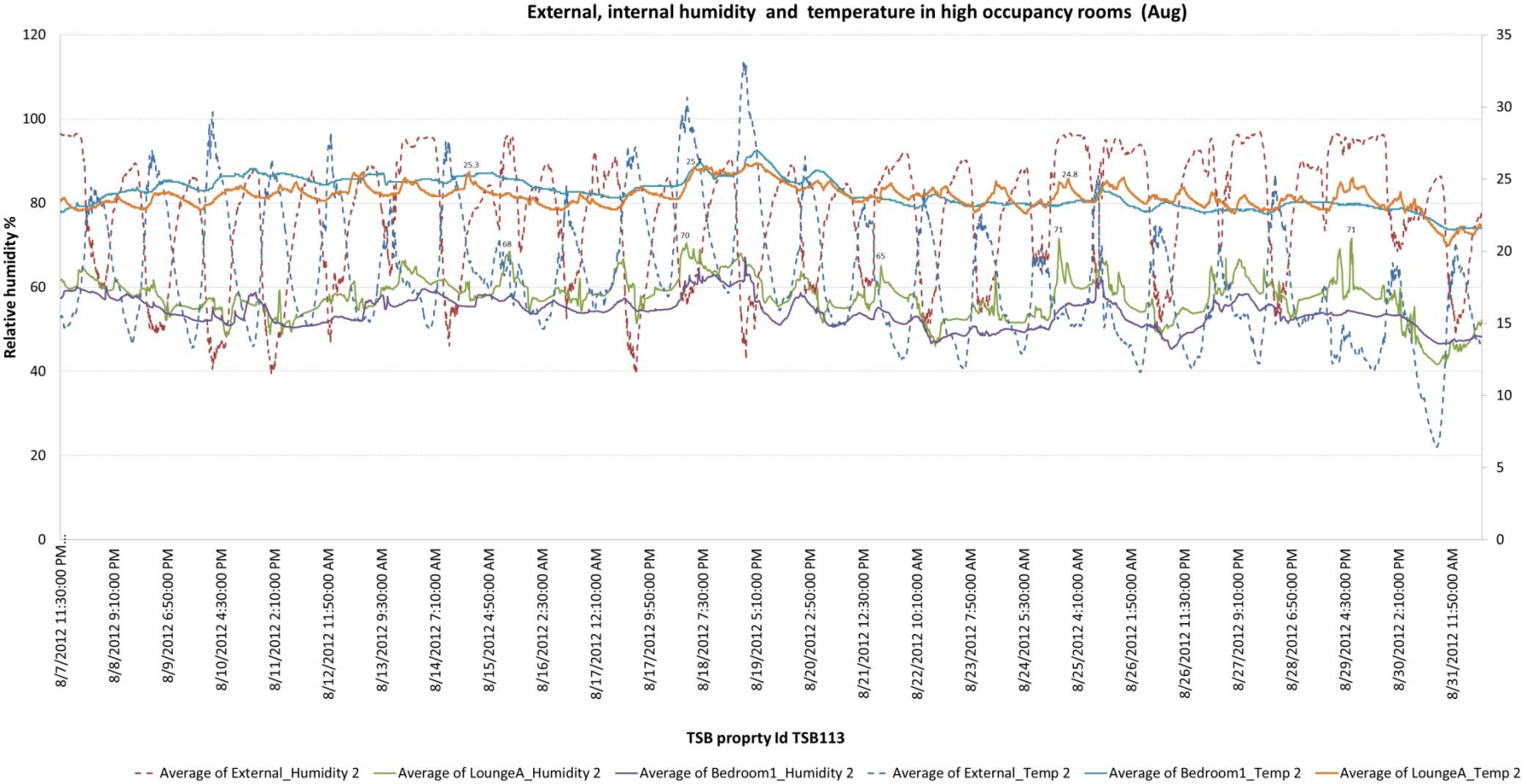


Figure 266: Window control practices in warm months (Aug). Case TSB113 temperature and humidity variation indicate windows opening in addition to the MVHR system operation.



Appendix 36 Figure 267: Internal and external temperatures in cases with MVHR ventilation system for the months of July and August.

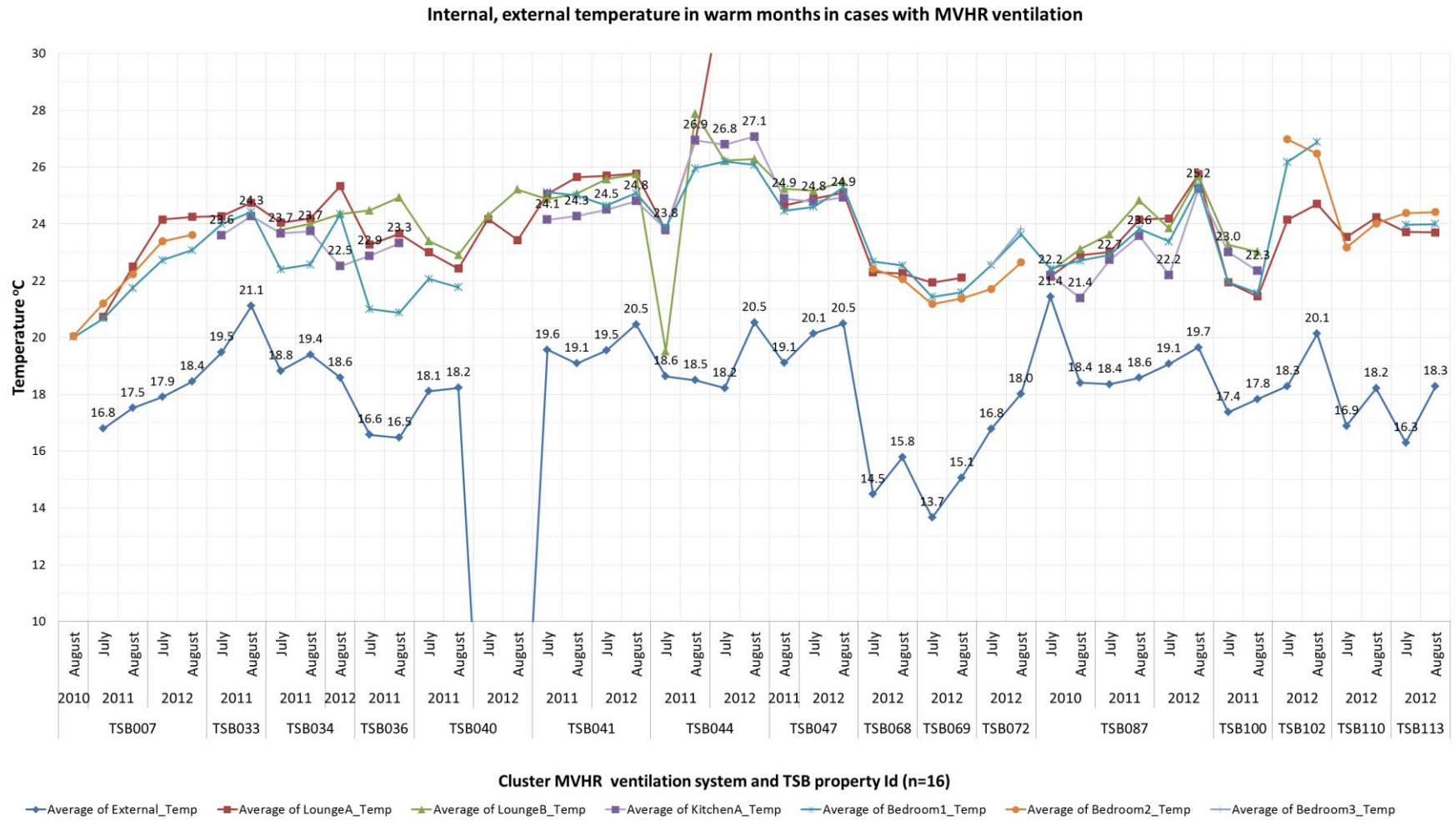


Figure 268: External, internal humidity and CO₂ levels in case of MVHR system in which occupants tend to interact with it by closing the air valves blowing cold air throughout the year.

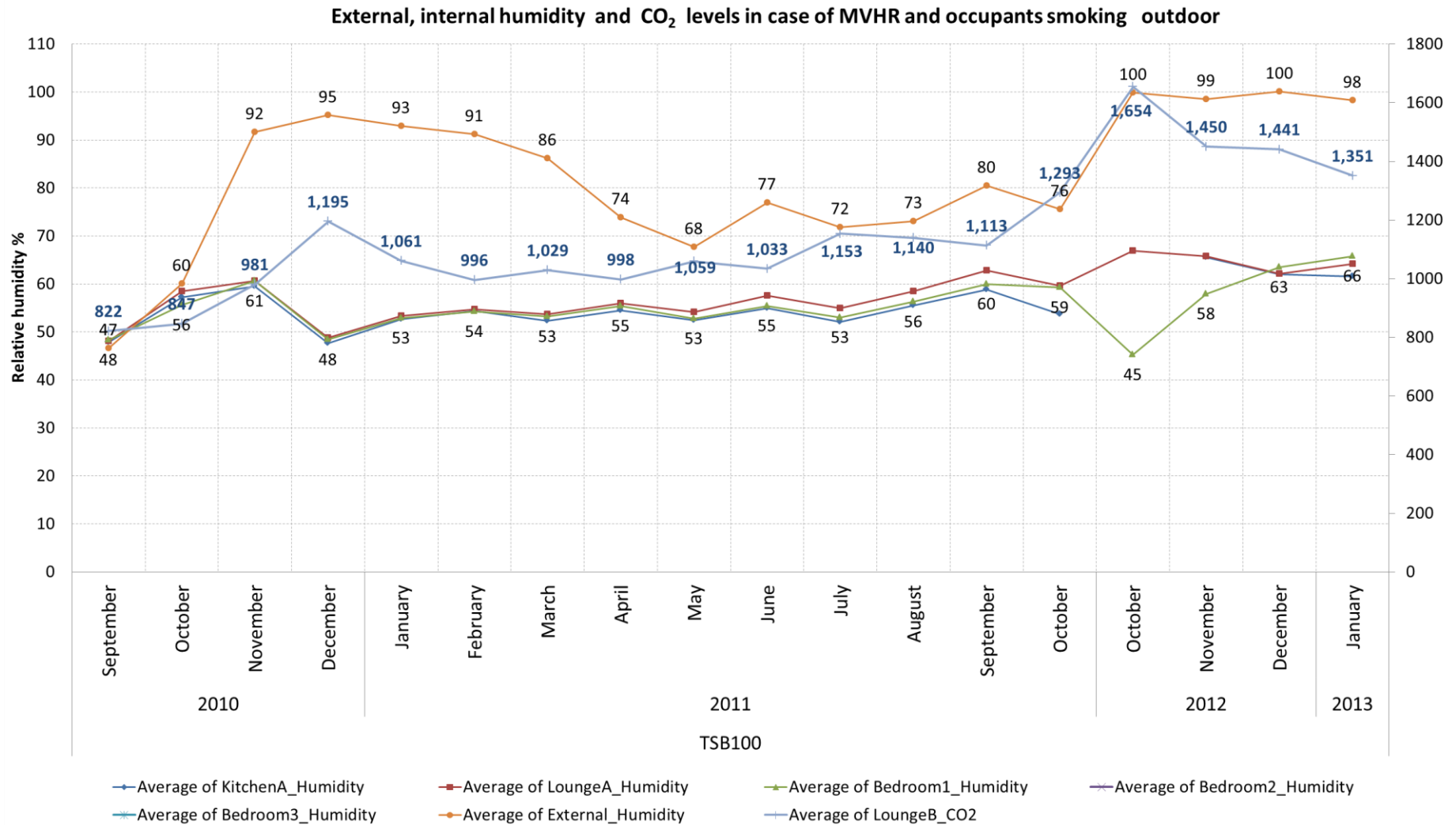


Figure 269: External, internal humidity and CO₂ levels in case of MVHR system and occupants interaction with windows in January to March (increased humidity in all rooms and CO₂ drop).

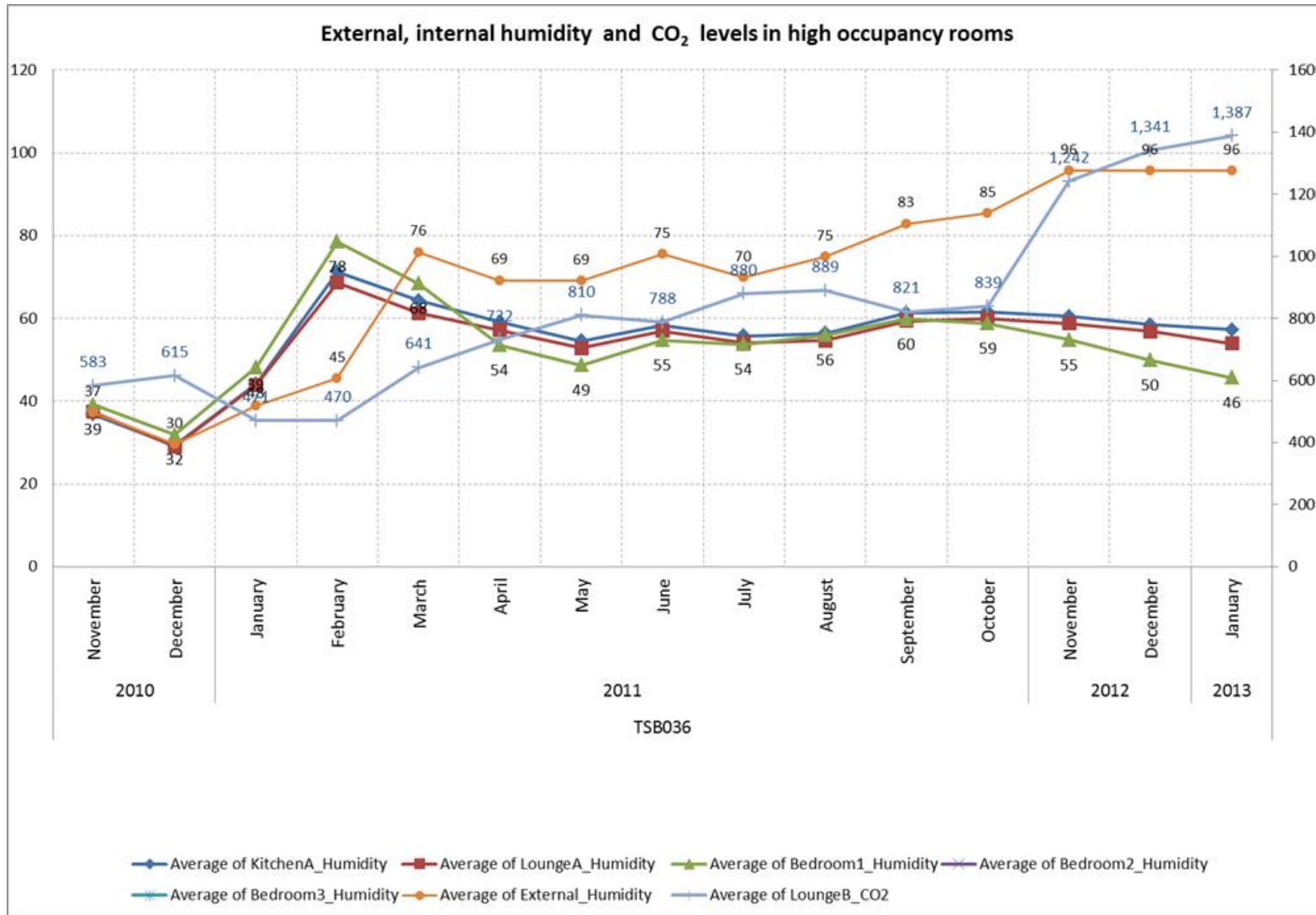


Figure 270: External, internal humidity and CO₂ levels in case of MVHR system in which occupants' adaptive behaviour changes in relation to post-refurbished living experience in the property.

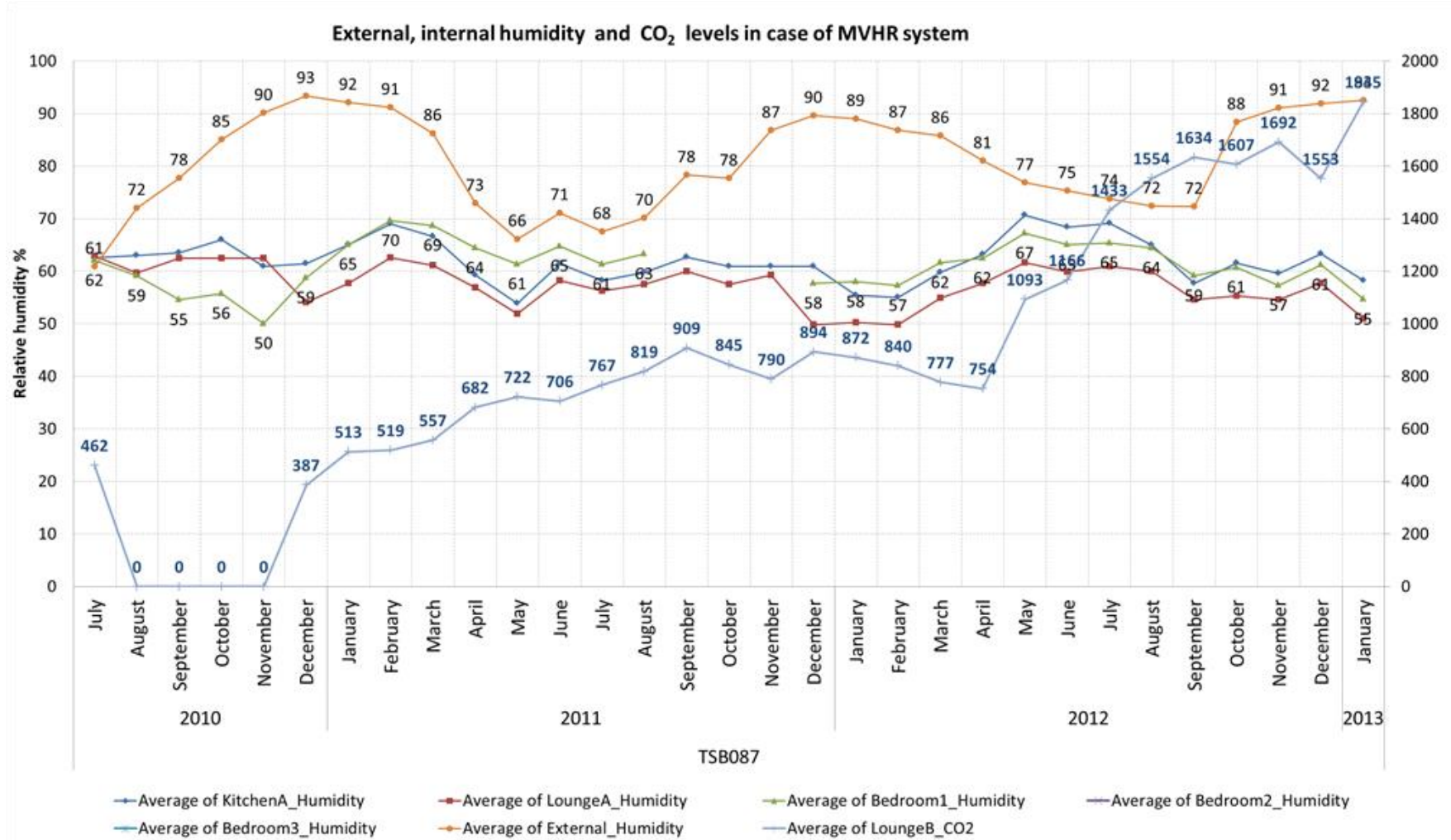


Figure 271: External, internal humidity and CO₂ levels in case of MVHR system and occupants interaction with windows especially in the nigh zone main bedroom.

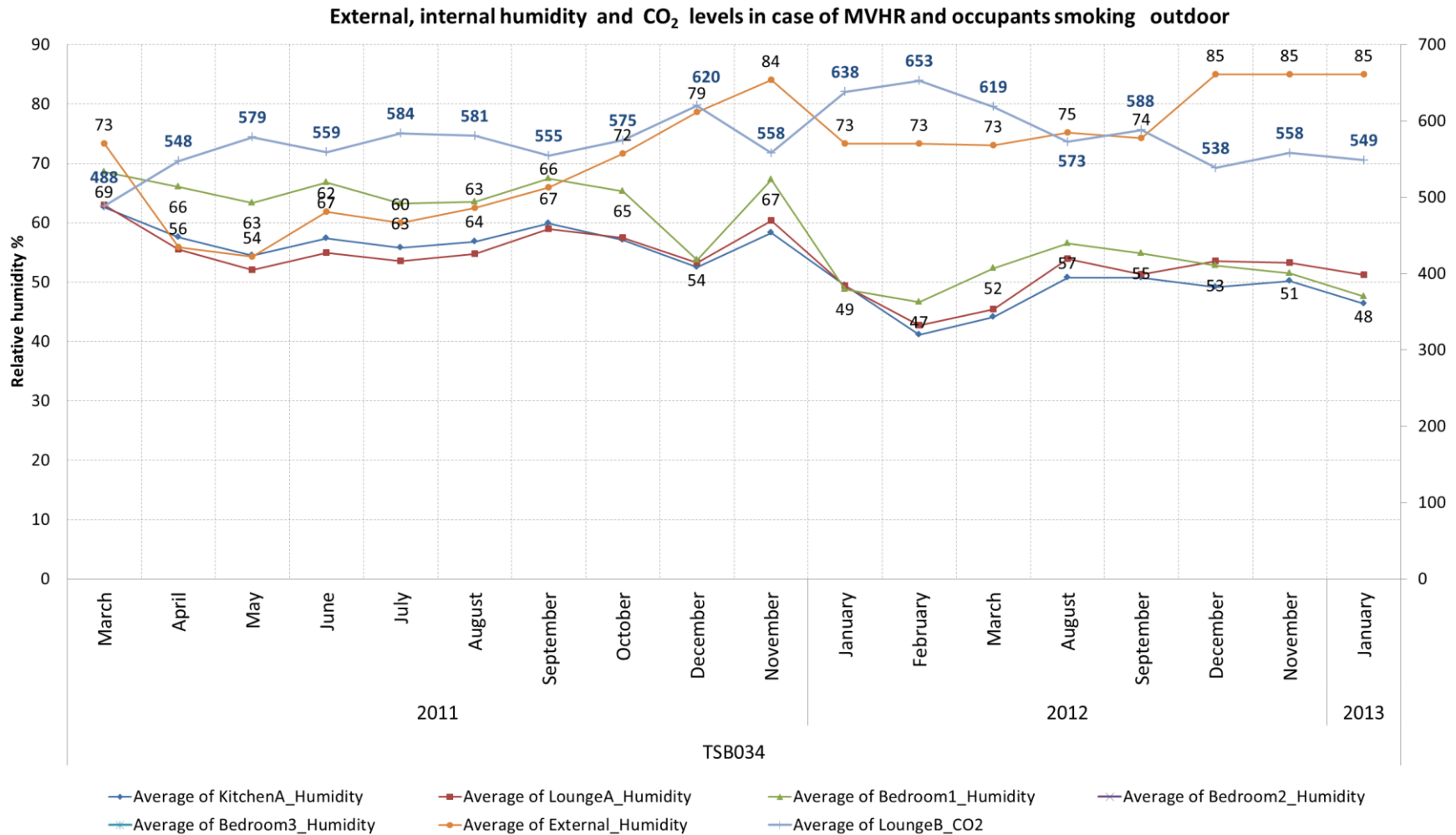


Figure 272: External, internal humidity and CO₂ levels in case of MEV, occupants' indoor smoking habits and their interaction with windows.

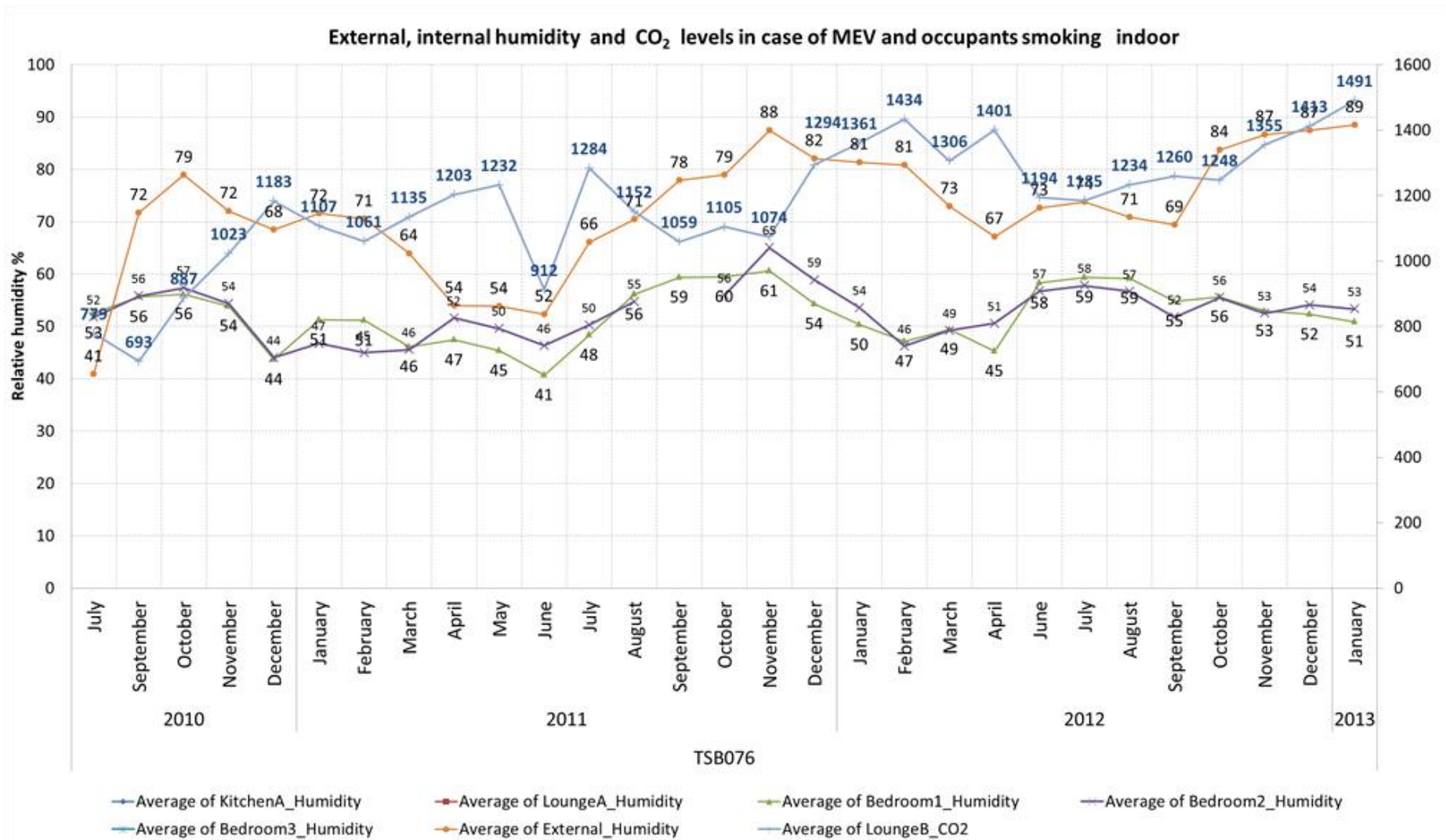


Figure 273: External, internal humidity and CO₂ levels in case of MVHR, high number of occupants and windows shut both in warm and cold months.

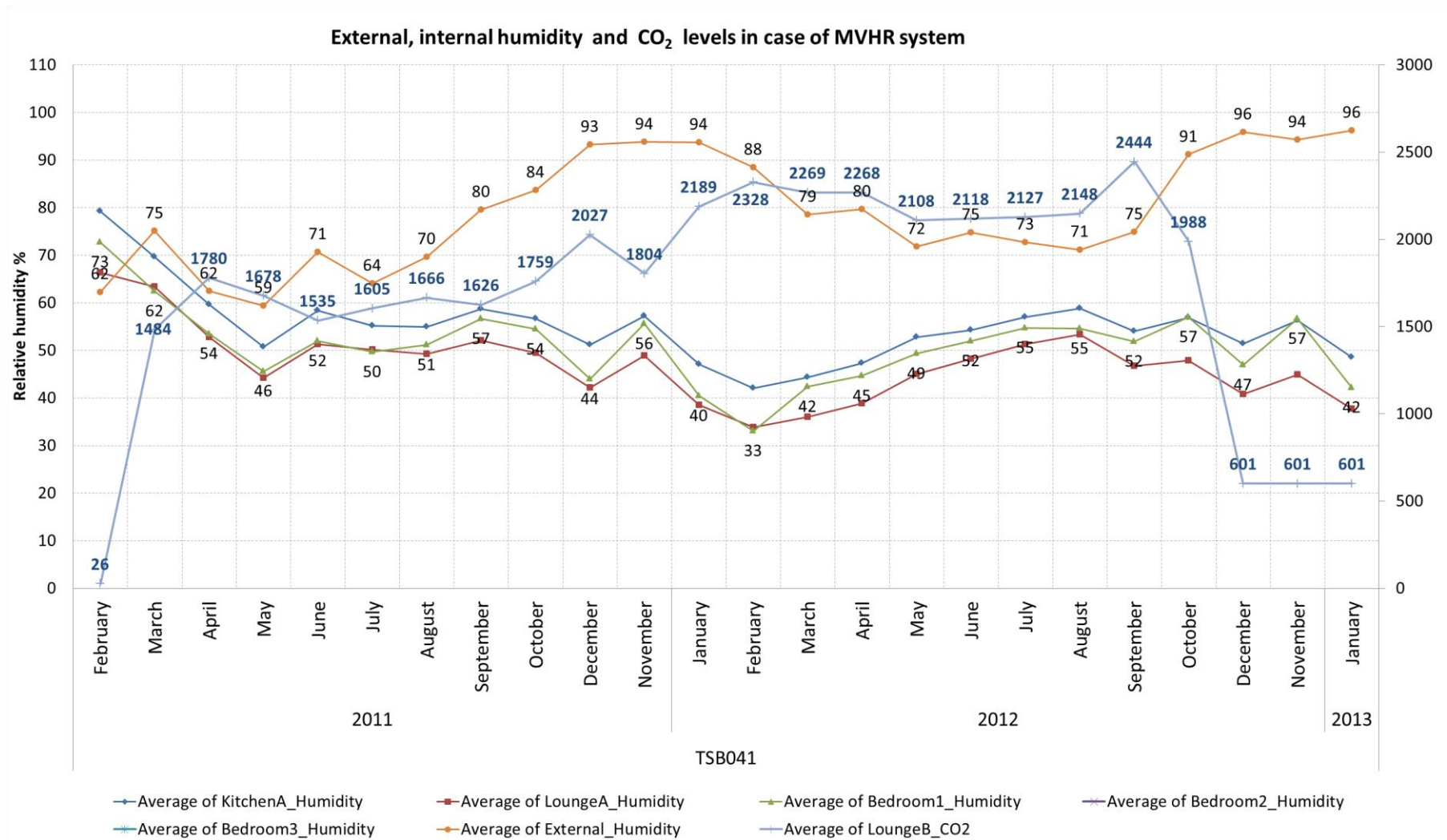


Figure 274: External, internal humidity and CO₂ levels in case of MVHR and occupants having some windows open all the time during cold months and once a day in warm months.

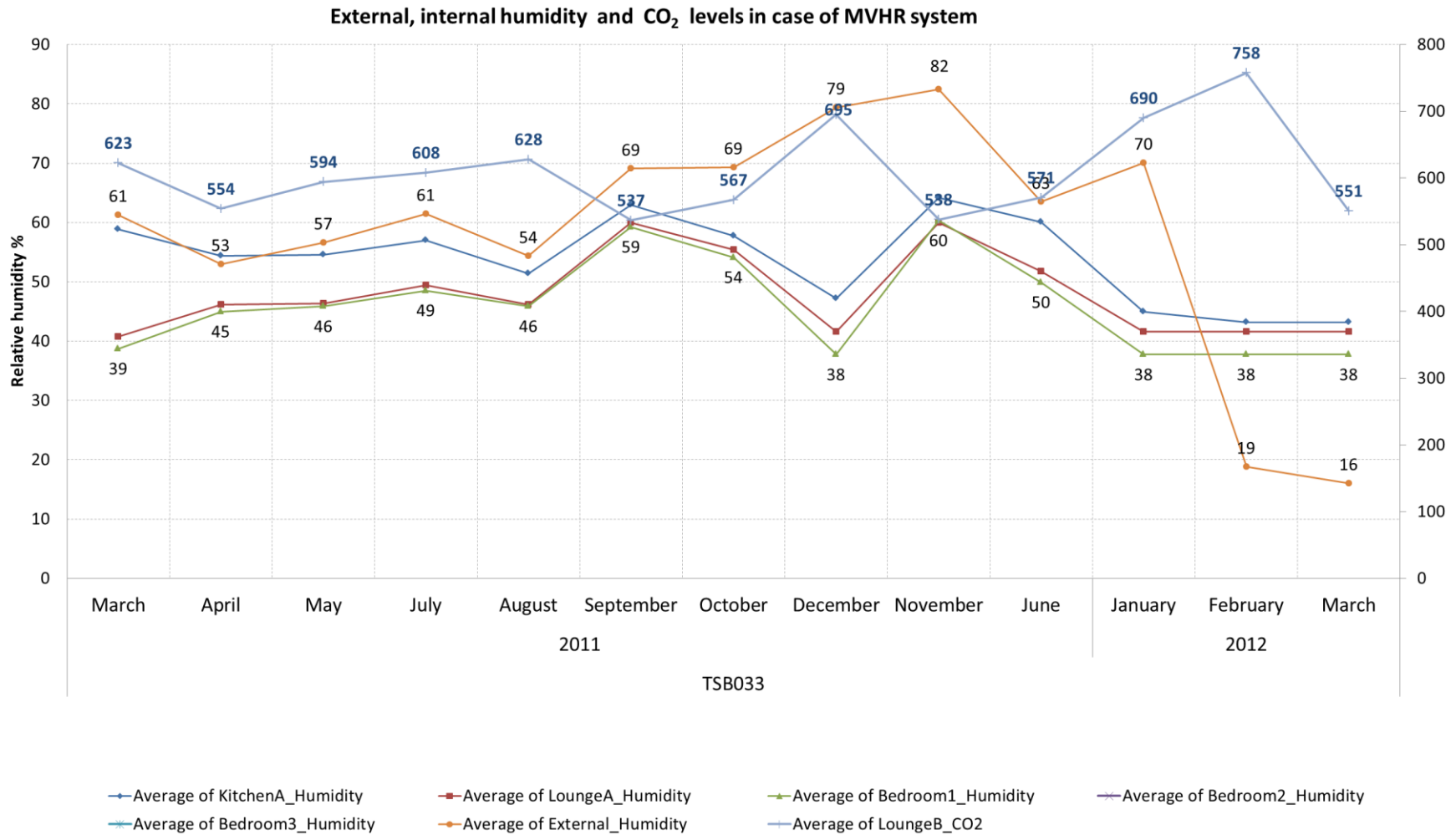
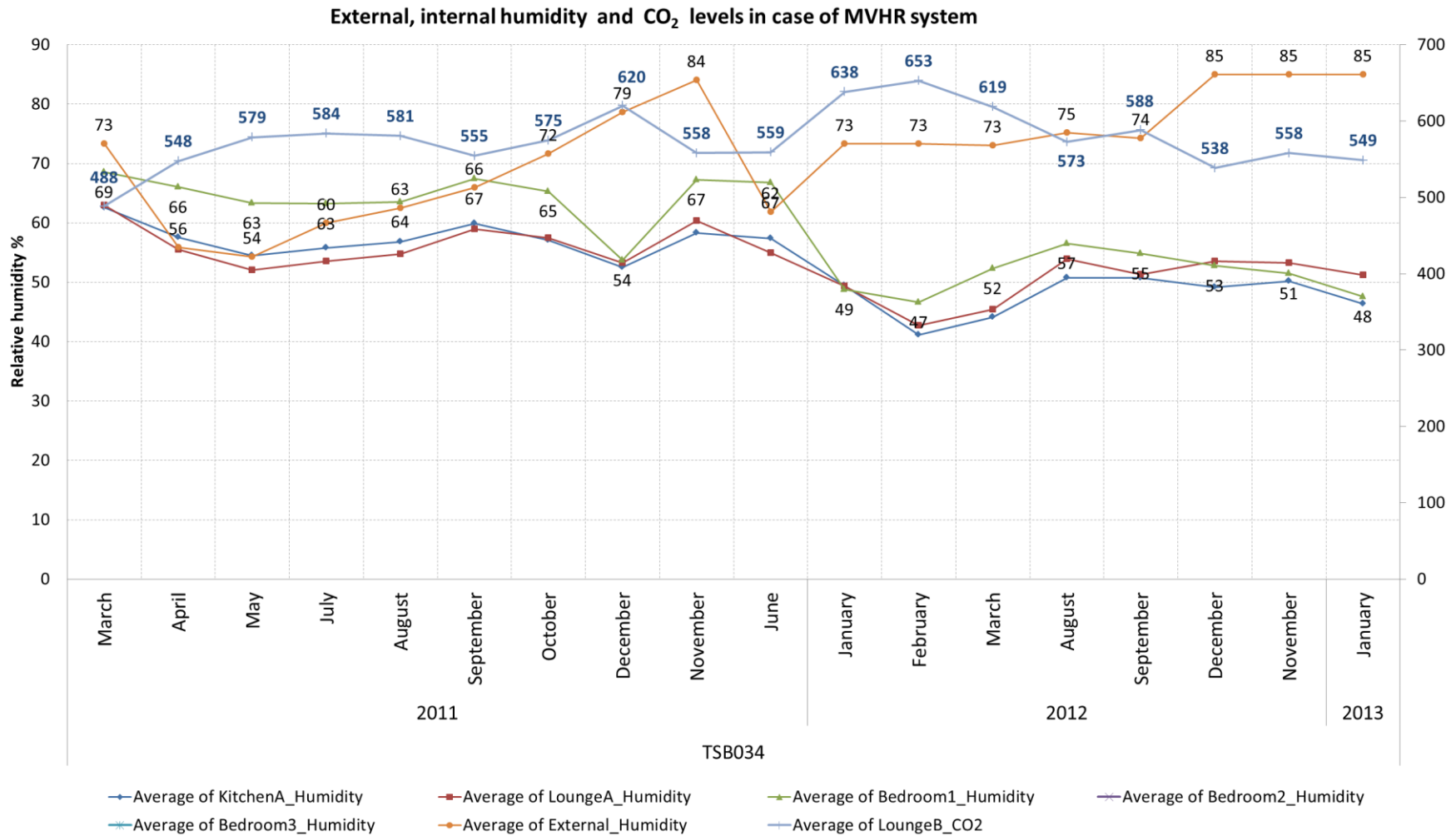
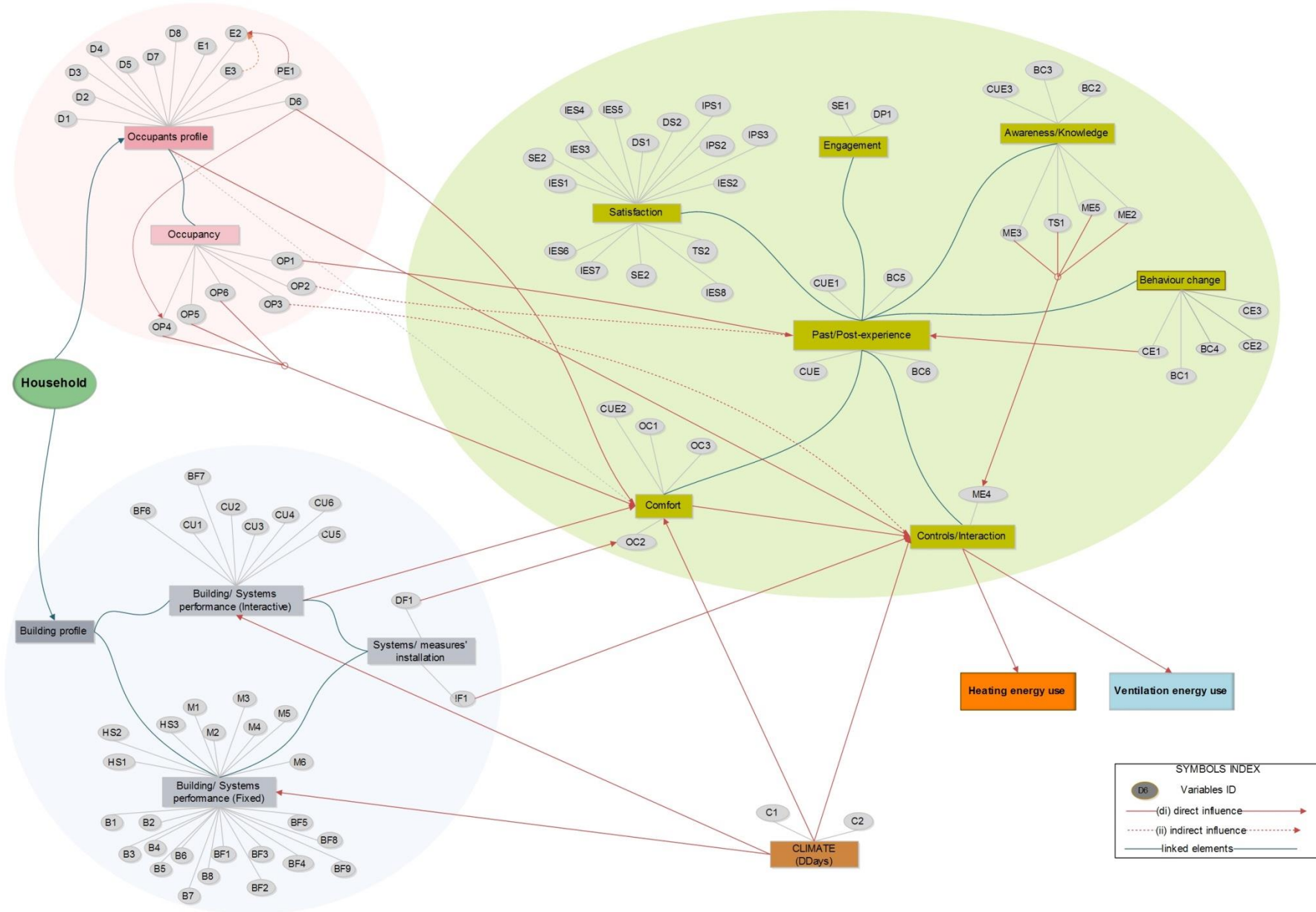


Figure 275: External, internal humidity and CO₂ levels in case of MVHR and occupants having windows shut during cold months and all windows opened once a day in warm months.



Appendix 37 Correlations between technical and non-technical variables in users' interaction with low-carbon measures as emerged from the RfF sample.

(ID) VARIABLES INDEX	
Occupants profile	(D1) Occup.Num . (D2) Gender (D3) Age group (D4) Family composition (D5) Cultural background (D6) Health conditions (D7) Smoking (D8) Pets (E1) Education/ Qualifications (E2) Occupation (E3) Income (PE1) Bills payment
Occupancy	(OP1) Occupancy background (OP2) Relocated during works (OP3) Living period in RfF property (OP4) Average occupancy in typical Week (Mon-Fri) (OP5) Average occupancy per Weekends (Sut-Sun) (OP6) Average occupancy annually
Building/ Systems performance (Fixed)	(C1) Building Orientation (C2) External temperature (B1) Building Status (B2) Age (B3) Type (B4) Tot. floor area (B5) Storeys (B6) Number of rooms (B7) Space layout (B8) Extensions/porches/conservatories (BF1) External walls (BF2) Ext. Walls finish (BF3) Partition walls (BF4) Roof /Loft (BF5) Floors (BF6) Windows (BF7) External doors (BF8) External shading Devices (BF9) Level of intervention (HS1) Heating system (HS2) Heating space (HS3) Heating Hot water (M1) Condensing Boiler (M2) Solar panels (M3) MVHR/Fans (M4) Solar PV (M5) Sun pipe light (M6) Intelligent control systems
Systems/ measures' installation	(DF1) Design faults (IF1) Installation faults
Building/ Systems performance (Interactive)	(CU1) Natural ventilation Windows (Control and use Summer) (CU2) Natural ventilation Windows (Control and use Winter) (CU3) Natural ventilation Doors (Control and use) (CU4) Heating controls (CU5) Natural lighting controls (Control and use) (CU6) Mechanical ventilation (Control and use)
Past/Post-experience	(BC5) Pre-installation level of occupant EE behaviour (BC6) Post-installation level of occupant EE behaviour (CUE3) Understanding of previous heating controls (CUE1) Opinion of the property prior to installations
Satisfaction	(IES1) Property condition (IES2) Health effects from property conditions (IES3) Draughts (IES4) Damp/ mould/ internal air quality (IES5) Smell (IES6) Natural Light (IES7) Noise (IES8) Security (DS1) Overall design (DS2) Change room sizes (SE2) Satisfaction with the process (IPS1) Improvements designed, as build (IPS2) Process (duration/ disruption/ cleanliness) (TS2) Level of instruction Satisfaction level (IPS3) Overall satisfaction with the property after refurbishment
Comfort	(CUE2)Com fort level of the property prior to installation (OC1) Overall comfort (Temperature) (OC2) Overall comfort (To cool down) (OC3) Overall comfort (To warm up)
Engage ment	(DP1) Tenants participation in design (SE1) Support of the RfF refurbishment process
Awareness/ Knowledge	(BC2) Awareness of energy of electricity and gas usage (BC3) Awareness of the retrofiting process (CUE3) Understanding of previous heating controls (TS1) Instructions/training (Type) (ME2) Training provided (measure) (ME3) Understanding purpose of the measure(s) (ME5) Understanding Actions affecting measure performance
Behaviour change	(BC1) Energy saving changes, Level of Green lifestyle (BC4) Behaviour change due to monitoring (ME1) Opinion of the measure (ME4) Level of control (usage) measures (CE1) Change in energy bills



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