# Low-carbon refurbishments: How passive or active are technologies, users and their interaction



Marina Topouzi
University of Oxford

# Low-carbon refurbishments: How passive or active are technologies, users and their interaction?

Marina Topouzi
Environmental Change Institute
University of Oxford
South Parks Road
Oxford OX1 3QY
United Kingdom
marina.topouzi@ouce.ox.ac.uk

## Keywords

refurbishment, interaction, low-carbon buildings, user behaviour, socio-technical, heating, ventilation, passive/active measures, low-carbon technologies

## Abstract

Current regulatory and other policy trends in housing refurbishments relating to low-carbon performance standards involve complex technologies and systems as well as innovative solutions to achieve the UK's demanding targets. Performance indicators of domestic refurbishments in general tend to rely heavily upon assumptions of ideal performance of materials, combined systems installed to high standards under specific conditions, and ideal occupant behaviour in operating and interacting with them. Previous studies exploring the influence of socio-technical factors on the UK's domestic energy use highlight that one of the main reasons for limited success in achieving energy targets is the lack of understanding of how people interact with domestic technology.

Using a sample of nine low-carbon whole house retrofits in the UK this paper explores occupants' interaction with heating and ventilation measures as designed, installed and operated. The paper discusses the central phenomenon of interaction within three key areas: technical aspects (building fabric and systems), occupant (user) and interaction (energy use and operation). Using an interdisciplinary methodological approach qualitative and quantitative empirical data were explored together, cross-checking occupants' 'doings' and 'sayings'. The paper presents preliminary evidence-based findings showing the extent to which active measures as designed and installed have fostered direct interaction involving active users, as well as the tendency of passive low-carbon measures designed and installed for passive users to involve indirect interactions with active users in practice. The analysis of findings identifies significant factors in combined active and passive systems that are relevant to everyday practices of heat and ventilation interaction.

## Introduction

The main drivers in energy use are occupants' needs and behaviour, which are affected by buildings' physical characteristics (Hitchcock 1993, 1995). The amount of energy a household system consumes is directly dependent on the level at which the different types of services (e.g. space heating, hot water and lighting) are required by the occupant, along with the level of efficiency with which these services can be provided. Exploring the influence of socio-technical factors on the UK's energy use, Lomas et al. (2006) highlight that one of the main reasons for limited success in achieving energy targets is the lack of understanding of how people interact with domestic technology. Current regulatory and other policy trends in housing refurbishments relating to low-carbon performance standards involve complex technologies and systems as well as innovative solutions to achieve the UK's ambitious targets. Households play a pivotal role in meeting the ambitious goal of reducing greenhouse gas emissions by 80 % (below 1990 levels) by 2050 (HM Government 2008). The need to retrofit existing homes on a massive scale 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 D.P. 2010). However, a large number of policy strategies, action programmes, regulations and standards for domestic refurbishments tend to rely heavily upon performance indicators that assume ideal behaviour of materials and of combined systems installed to high standards under specific conditions, as well as ideal occupant behaviour in operating and interacting with them.

In the current context of domestic energy studies there is a disciplinary bias in energy and behavioural model approaches. Technical approaches rely heavily on 'average', 'default' or 'typical' user (occupant) profiles to estimate energy use (Cramer et al. 1984; Lutzenhiser and Bender 2008; Yao and Steemers 2005), failing to adequately take into account actual user interaction that differs from average profiles. Similarly, behavioural models rely heavily on conceptual approaches and theoretical frameworks that view energy use solely in terms of behavioural and economic factors. Both models, due to methodological constraints and lack of data, do not investigate household energy consumption holistically. The process of deep refurbishment of an existing building system, with passive (or active) design solutions and installation of innovative technologies and control systems is currently at a preliminary stage. There is still very little evidence at the in-use stage showing whether low-carbon refurbishment interventions and systems' components can holistically and efficiently perform together as designed (or modelled) and as built (or 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 among occupants, building systems and unfamiliar technologies.

The main research question that this paper addresses is: What type of interaction(s) (direct/indirect, passive/active) exist between deep retrofitting interventions and occupants' behaviour? The overall intent is to explore the type of interactions between social occupants and low-carbon building systems in heating and ventilation. The challenge in the selected sample was both in the type of occupants living in the properties and in the low-carbon interventions undertaken in the buildings. Within the UK housing stock local Councils or Housing Associations give priority to certain categories of social tenants that involve different vulnerability characteristics. In this study such characteristics like certain allocation factors related to tenants' health issues, single parenting and demographic and economic characteristics (e.g. unemployment and social benefits) are all aspects highly related to occupancy patterns in a building. These, together with different levels of design participation and purchasing, are some of the factors contributing to different types of usage compared to other social groups (e.g. private tenants). Moreover, technical factors of low-carbon deep refurbishment interventions in this type of housing stock certainly have different implications and challenges compared to new build. The paper uses an interdisciplinary methodological approach that involves cross-checking of the qualitative and quantitative data to reduce the distance between occupants' 'doings' and 'sayings' and to highlight some of the factors which affect occupants' practices. These include the design of the technologies and installation of the measures, type and time of occupancy, physiological preferences linked with the health of the occupants, psychological and behavioural aspects related to comfort along with the needs for safety and privacy, previous residential experience and occupants' knowledge.

#### INTERDISCIPLINARY APPROACH

Given the complex and subjective nature of socio-technical factors, the study developed an interdisciplinary methodological approach in which the research question and objectives explored user 'interactions' 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. The purpose of this conceptual framework was to map the courses of action, giving the different approaches empirical coherence. This framework incorporates elements borrowed from existing established social theories, previous interdisciplinary technical and socio-technical research and established methodological approaches.

In the study's approach to refurbishment interventions and occupants, a system of practices is structured in which agents, interactions and individual user behaviour are combined to determine a building's overall performance. The notion of 'interaction' is used in the study to define control-oriented actions between occupants' routinised behaviours and elements of the building system and the environment. Aggregated, these interactions influence occupants' wellbeing, health conditions and comfort at a certain moment in time and determine occupants' interaction with their environment over time (Bluyssen 2009). The complexity of user interaction and the interrelation of factors involved in this study required a combination of theories to identify the actual use and keep the research objective and empirical inquiry coherent.

In this respect the theoretical approaches used in this study are seen as different viewpoints that complement one another by looking at the same thing (interaction and energy use) using varying levels of detail. Specifically the main principles of the 'user-centred'(Vischer 2008) theory were used in the study's overarching theoretical approaches to link the information generated by the systematic empirical building performance evaluation (BPE) methods. The user-centred theory as applied in the study accepts that the building environment exists to support the activities of the users that it shelters; therefore, in each household variables and factors related to the identities and activities of the user(s) were thoroughly examined. The empirical material presented in this paper is mainly linked with principles of the 'user-centred' theory concerning users' experience (past and post) on the route to learning about the building environment. Based on the theoretical socio-technical perspectives 'interactive adaptivity' was used in the study to draw attention to particular events of interaction. Using the broader definition of 'adaptation', the conceptual framework of this research uses the assumption of adaptive approaches according to which occupants are not passive recipients of the environment – especially when changes occur – but interact with it using different ways to restore and achieve their conditions of comfort. In this context Nicol and Humphreys (2002) argue:

> if a change occurs such as to produce discomfort, people react in ways which tend to restore comfort. (p. 564)

The interactive adaptivity approach moves forward from the previous user-centred considerations by focussing on particular actions that occupant are carrying out to create their new (post-construction) microenvironment. In this respect the Science, Technology and Society theory was utilised to illuminate the type and extent of interaction that is 'scripted' by the low-carbon measures and the technologies installed in the refurbished properties. The study, following concepts that by now are familiar in the field (e.g. Akrich 1992; Shove 2003), is focussed on what is 'closed' or 'open' scripted (prescribed, prefigured or not) by the technical intervention, and what level of interaction is left to users (occupants) to create their own microenvironment. In occupants' interactions with the building system such approaches allow observers to identify how passive or active measures and users are. Finally, the study also borrowed elements from practice theory (such as know-how and embodied habits, institutionalised knowledge, engagement and technologies), as defined in the empirical study of Gram-Hanssen (2009, 2010) on households' energy consumption. These elements helped to identify occupant routines and technological structures that contribute to a household's energy consumption practices.

## METHODS

The empirical sample presented in this paper is a segment of a larger sample of on-going doctoral research. The analysis in progress involves 9 retrofitted properties clustered by building type (Figure 1) and location. The data sample consisted of low-rise social refurbished houses in the South East of England involved in the Retrofit for the Future (RfF) competition programme organised by the Technology Strategy Board (TSB).

Methodological approaches and tools from BPE and post-occupancy evaluation (POE) studies were used to evaluate the distance between a building's environment and a system's actual performance (in-use) compared to the performance as designed. The data collection consisted of physical and behavioural determinants and 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 focussed on behavioural aspects related to usage (interaction) and systems controls using in-depth semi-structured interviews with the householders and observational methods (POE techniques) at the retrofitted properties. To overcome limitations from self-reporting bias, the study's interactive design uses methodological triangulation to converge quantitative (numeric) and qualitative (narrative text and images) data. This allows correlation of occupants' 'doings' and 'sayings' by linking the quantitative energy data with users' actual practices, broadening the interpretation of complex socio-technical variables in the sample. This has involved multiple techniques (e.g. semi-structured interviews along with monitoring measurements and spot checks), varied data sources and distinct methods of analysis and theories.

The empirical analysis presented in this paper explored 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). It has used thematic analysis to explore themes (e.g. comfort controls) and sub-themes (e.g. type of heating controls). The selected theories from the study's conceptual framework also had an important role in linking variables and the different types of data and explaining events and practices that initially can look unrelated. For example, they defined the nature of determinants of interaction (e.g. direct/indirect control of windows, passive/active interaction) to classify the technical building components and occupant (user). Given that in this research socio-technical correlations in interaction are explored within a small number of cases, findings cannot be treated as statistical generalisations or generalised outcomes for the whole RfF competition programme. Instead they need to be seen as the results of empirical evidence-based indicators of interaction between occupants (households) and low-carbon measures.

## BUILDING PROFILE: TECHNICAL FACTORS

In the next section the building profile outlines key information in terms of the designed/installed physical determinants for the selected sample.

### Building context and building fabric

The properties in the sample are two story mid- and end-terraces as well as semi-detached houses of 2, 3 and 5 bedrooms located in residential areas. The size of the properties varies between a minimum of 62 m$^2$ to a maximum of 126 m$^2$. The house layout is that of the UK's typical two floor semi-detached houses and terraces, with the living area on the ground floor and with the sleeping area on the first floor. The larger properties in the sample also include a bedroom on the ground floor (Figure 1).

Deep refurbishment (DR) interventions (Table 1) were undertaken in all properties except in two cases where the level of intervention is between typical and deep refurbishment. In 6 properties the intervention also involved changes in the layout with opening space between rooms or extensions to improve indoor comfort.

The design strategies undertaken in the 9 properties involved a number of low-carbon interventions to improve the previous poor condition of both building fabric and existing systems (e.g. walls, loft insulation, heating/ventilation systems, glazing system, etc. – Table 2).

Key issues considered in the intervention strategies in the properties were related to the inadequate insulation of the fabric with significant air leakages, draughts and damp. The lack of airtightness and inefficiency of the previous systems had entailed poor comfort levels, with variation of extreme temperatures between rooms and floors, and unaffordable heating consumption costs for many of the occupants. The insulation strategy also included innovative materials and thick layers of roof insulation for existing buildings' fabric and extensions. In 5 of 9 cases, despite standards' guidelines and the significant impact they have on performance, ground floor insulation was not installed. Regarding the openings, windows were replaced in all properties with either triple or double glazing systems with high performance specifications. Not in all properties (7 of 9 cases) the external doors were replaced and in 3 of 7 cases this is standard/average to poor quality rather than high standard as was initially intended by the competition's 'whole building approach'. Although building fabric insulation factors (U-value, thermal bridging) are particularly significant, having a direct impact on the overall building's heating energy use, they have a passive role – 'fixed' – in terms of occupants' interaction (Topouzi 2011). Occupants cannot directly interact with the insulation characteristics, but their comfort control actions over systems (e.g. openings, heating systems) have a direct on the building fabric's actual performance. Consequently, heating occupants' interaction with the low-carbon physical elements is described only by the actions

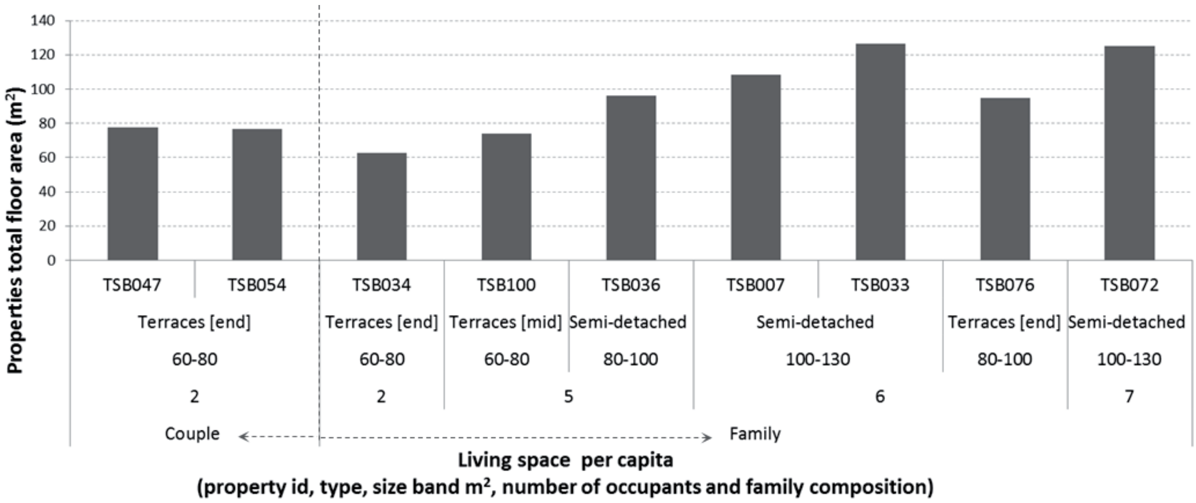


*Figure 1. Buildings' characteristics in the sample.*

**Table 1. Classification of the level of refurbishment interventions in the RfF sample.**

| Level of intervention | Low-carbon improvement description | Compliance |
|---|---|---|
| **(DR)** Deep Refurbishment (or deep retrofit) | Insulation (floor, wall, loft, windows), space and water heating system, day lighting, ventilation and space cooling, renewable 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 Dwelling Building, Warm Homes standard, Decent homes standard |

**Table 2. Level of intervention and systems installed.**

| Systems and measures installed | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Renewables | | | | | Active Vent. | Controls | Level of intervention* |
| Cases (TSB id) | Boiler | Heat pumps | micro-CHP | Solar panels | Solar PV | System | Intelligent control systems | |
| 034 | | | CHP | | | MVHR | Wattbox | **TR - DR** |
| 007 | | ASHP | | Solar panels | | MVHR | | **DR** |
| 036 | | GSHP | | | Solar PV | MVHR | Wattbox | **DR** |
| 054 | Cond. Boiler | | | Solar panels | Solar PV | MVHR | | **DR** |
| 033 | | ASHP | | | Solar PV | MVHR | Wattbox | **DR** |
| 076 | Combi Boiler | GSHP | | | Solar PV | | Wattbox | **TR – DR** |
| 100 | | | CHP | Solar panels | Solar PV | MVHR | Wattbox | **DR** |
| 047 | | | CHP | | Solar PV | MVHR | Wattbox | **DR** |
| 072 | Cond. Boiler | | | Solar panels | | MVHR | | **DR** |

**Abbreviation used for the level of intervention as described in Table 1.*

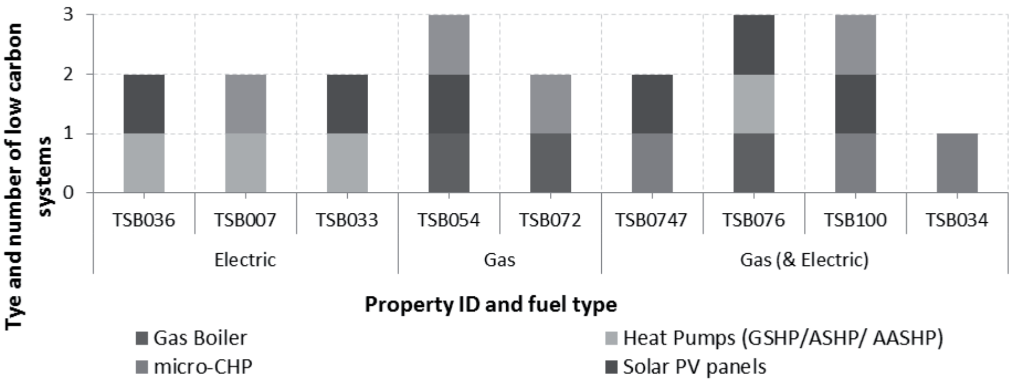


*Figure 2. Heating systems installed.*

taken over heating systems via measures (e.g. programmer, radiators' thermostatic radiator valves (TRVs), etc.), as well as over the openings via windows and doors.

**Building systems**

Before the refurbishment works the 9 properties had central heating systems and the fuel used in the houses varied from coal to gas and electricity. The previous heating source and controls in the properties were radiators (with or without TRVs) or storage heaters controlled mainly by thermostats and programmers. In many properties the poor fabric condition enforced the use of secondary heating sources like open fireplaces, gas stoves and electric heaters in the cold months and ventilation fans during the hot days.

The fuel strategy in the properties after refurbishment is mains gas and electricity. The systems installed for space heating and hot water are illustrated in Figure 2. The diagram shows that in 5 properties the heating and hot water is provided by one system (e.g. micro-Combined Heat and Power (CHP), heat pumps or boilers), whereas in the rest it is provided by a combination of these systems with solar thermal as a backup for the hotter months with increased solar radiation.

To understand user's interaction with heating and ventilation systems and fabric components (e.g. openings) it was important to define how 'scripted' or not the overall design systems and components were before and after installation. This allowed subsequent evaluation of how 'active'[1] or 'passive' their users' actual operation is.

From a technical perspective Table 3 shows to what extent the interaction was initially 'scripted' by the measures at the design stage in the refurbished properties. For all systems the interaction with the 'scripted' measures' controls was designed for either direct or indirect use. Therefore, in heating systems direct controls on gas boilers were designed for active users, whereas in 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. In one case a Mechanical Ventilation with Heat Recovery (MVHR) system was installed as the heating source operated directly by an intelligent control panel and indirectly from the MVHR filter vents regulating the intensity of the blown air.

Similar to the heating controls are the measures designed for the hot water systems, whereas for the properties with combined systems of gas boiler, HP or CHP and solar thermal there is no direct control but only indirect operation from systems' controls.

There are no 'scripted' constraints (e.g. fixed windows or doors) affecting openings operation in passive ventilation. As regards the active ventilation MVHR was installed in 8 properties. Direct MVHR unit controls are not provided in any of the properties, while indirect controls operate through the MVHR control panel, boost button and filter controls provided for active users. At the design stage the indirect impact from the operation of windows and doors in the MVHR systems has considered passive usage in both cooler and warmer seasons.

## OCCUPANTS' PROFILE: SOCIAL FACTORS

This section provides the building context 'as occupied' including occupancy and socio-demographic factors related to occupants' interactions. Except for two properties with elderly couples (age group 65+) and a family of a mother and son the family compositions in the rest of the sample are young families (age group 30s–50s) with children. A factor that was found to affect occupants' post-experience in the sample is households' occupancy background (past-experience) with RfF houses, and whether they were occupants before the installation works or moved in after the low-carbon works finished. Although the past-experience living period in the RfF property can vary between the two groups (occupants before or after), for 9 cases the post-occupancy experience in the refurbished property up to the day of the interview was from 5 months to over 1 year. The main allocation factors for moving into the refurbished property were for some cases occupants' health conditions and their needs for a different size of property.

Householders' occupational status varies in the sample (full time, part time or retired/not working). For more than half of

1. The study uses the terms 'active' and 'passive' users to describe the level of occupants' interaction with the heating and ventilation systems, whether this is prefigured by the technology and measures or by occupants' (users') practices. The level of interaction defined by the control a user has over a measure uses an evaluation scale of interaction/control (1=Full interaction/control, 2=Good, 3=Mixed, 4=Poor, 5=No interaction/control), in which users are classified as 'active' when they have control over a measure or a system (act: scale levels 1, 2), as 'passive' users when they do not have any control (pass: scale levels 4, 5) and as neither active nor passive when they have mixed controls/interaction (act/pass: scale level 3).

**Table 3. Systems and measures controls as designed/ installed (n=9 buildings).**

| Systems' direct/ indirect operation via measures' controls | | | Designed for … |
|---|---|---|---|
| Heating | | | |
| *Space* | **Gas boiler:** | ***D*** via Gas boiler controls<br>***I*** via thermostat, programmer, TRVs | ***Act:*** Gas boiler controls, Thermostat, Programmer, TRVs, Intelligent control systems *(Wattbox, Optima Design Controller)*<br>***Pass:*** CHP boiler controls, Heat pump boiler controls, TRVs, MVHR fan controls |
| | **micro-CHP:** | ***D*** via CHP boiler controls<br>***I via*** Intelligent control systems *(Wattbox)*, TRVs | |
| | **Heat pumps:** | ***D*** via Heat pumps boiler controls<br>***I via*** Intelligent control systems (Optima Design Controller), MVHR fan controls, *TRVs* | |
| *Hot water* | **Gas boiler:** | ***D*** via Gas boiler controls<br>***I via*** Programmer, Intelligent control systems (*Wattbox*) | ***Act:*** Gas boiler controls, Programmer, Intelligent control systems *(Wattbox, Optima Design Controller)*<br>***Pass:*** CHP boiler controls, Heat pump boiler controls, Solar thermal panel controls |
| | **micro-CHP:** | ***D*** via CHP boiler controls<br>***I via*** Intelligent control systems (*Wattbox*) | |
| | **Heat pumps:** | ***D*** via Heat pump boiler controls<br>***I via*** Intelligent control systems (*Wattbox*) | |
| | **Solar thermal:** | ***D*** via Solar thermal panel controls<br>***I via*** Intelligent control systems (*Wattbox*) | |
| Ventilation | | | |
| *Passive* | **Windows:** | ***D*** via Window operation<br>***I*** via Window filter vents, Door operation | ***Act:*** Window operation, Window filter vents, Door operation |
| | **Doors:** | ***D*** via Door operation<br>***I*** via Window operation | |
| *Active* | **MVHR:** | ***D*** via MVHR controls, Control panel, Boost button, Filter controls<br>***I*** via Window & Door operation | ***Act***: Control panel, Boost button, Filter controls, Fan ON/OFF switch<br>***Pass:*** MVHR controls, Fan & light one switch control, Window & Door operation |
| | **Electric Fans:** | ***D*** via Fan ON/OFF switch<br>***I*** via Fan & light one switch control, Window & Door operation | |

*D = Direct, I = Indirect, Act = Active Users, Pass = Passive Users.*

the cases the houses are occupied 24 hours/7 days a week; for the rest the occupancy pattern is around 15 to 17 hours per day. The occupancy time in the properties is highly correlated with heating and ventilation interaction and controls. The main factors affecting occupancy in the social housing properties are occupants' health conditions, as well as full time child caring often combined with unemployment. In terms of occupancy and use of space it appears from the interviews that the highly occupied area in all properties is the living area whereas bedrooms are used only during sleeping hours. Social roles and responsibilities along with individual factors shape the overall household's lifestyle. Therefore, factors identified affecting indoor comfort and $CO_2$ levels and consequently users' interaction with ventilation measures are occupants' smoking habits (4 households have one or more smoker occupants, half of them smoking indoors), as well as the number of pets that live in the house. Direct correlations between occupancy factors and occupants' past and post-experience in the property related to behaviour change variables are discussed in the following interaction profiles.

### BUILDING AS SOCIO-TECHNICAL SYSTEM AND CONCEPTUAL THEORIES

Occupants' interaction within the building system is discussed under the lens of the theories that comprise the study's conceptual framework. Focussing on the type of interaction (direct/indirect, passive/active) the following discussion first explores how past and post-experience prefigures the use of the building environment and second how systems and measures in heating and ventilation prefigure user interaction related to certain behavioural, psychological and physiological factors. Therefore, in this discussion principles of the user-centred theory are used to describe occupants' experience (past and post) in terms of interactive effects between occupants and the living space, building environment and systems. Particular events of interaction were highlighted by theoretical approaches to interactive adaptivity focussing on the behavioural, physiological and psychological factors that influence occupants' everyday practices of regulating heating and ventilation. In this the technology of the building environment and systems installed explores, under the lens of theoretical approaches in science and technology studies, the extent to which interaction was prefigured (or not) in the design and installation, or whether interaction has been re-prefigured (or re-defined) by occupants' operation. Finally, these types of interaction factors and relationships between elements of practice theory, like technology, habits/know-how, engagement and knowledge, show how practices in the new low-carbon environment hold together.

#### Occupants' past-interaction profile

In 7 of 9 properties, occupant's past-experience of the previous building environment, 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. Previous heating controls vary from the standard programmer and thermostats to electric storage heater controls. However, the poor indoor environments and systems had significantly affected occupants' past-experience of comfort levels, understanding of heating controls and awareness of energy cost. In the pre-retrofitted environment occupants' approaches to physiological and behaviour adaptation were in most cases unbalanced. Therefore, while their actions in responding to the building environment were to improve its performance by carrying out minor physical interventions to the building fabric – when allowed – their comfort controls were still restricted by financial factors and the building itself. Although such buildings' prior works may be considered active systems allowing occupants to interact with them, in practice it appears that the physical conditions have made occupants passive recipients with merely a few controls. Therefore, interactive effects at the pre-retrofit stage were largely scripted by the technology and products, as they were directly prefigured by factors like the physical condition of the building fabric and systems' age and type.

The uncomfortable conditions varied with extreme temperatures between rooms and floors, draughts, damp or cold bridges. Occupants describe themselves as having a passive role in terms of thermal comfort and controls. As reported of indoor conditions in cold months,

> … it was bloody freezing … we used to wear gloves, hats, scarfs and coats in the house … we had no choice … (Occ. TSB036)

Whereas other households could afford the cost these occupants had to run the heating at high temperatures of up to 25–30 °C all day, often using additional heating sources as the house turned cold very quickly. The poor building fabric had also limited occupants' interaction with windows as it was too cold to keep them open. However, there were a few cases (TSB047, 036, 054) where occupants, despite the cold environment, kept their comfort preferences and personal habits, sleeping with the windows open even in very cold days:

> … we've always slept even the coldest of days with the bedroom window open … because I like the cool air I don't like to sleep in warm bedroom I like to have a cold bedroom … (Occ. TSB036)

In warmer months occupants' past-experience in all households, involved frequent interaction with openings and the only factors limiting window operation were indirect factors like security and noise issues.

Concerning how the heating system and fabric influenced occupants' practices, at this pre-retrofit stage, this was more strongly related to routinised bodily and mental activities and their habits of operating heating controls and openings. However, in their routinised practices there was also a practical understanding and know-how allowing them to choose their habits consciously. Some of them for instance did not open the windows and kept all the doors closed during cold months to prevent heat losses, whereas others even on cold days slept with the bedroom window open. It appears that occupants' financial interest in saving energy and maintaining sufficient comfort levels engaged occupants' practices related to the heating and indoor climate.

#### As built/in-use: Occupants' post-interaction profile

Overall, occupants were satisfied with living in the property after the low-carbon improvements in all cases except from one. In 3 of 9 properties occupants seemed to have a mixed understanding about the measures and be confused about what each specific technology does, how it works and what it can offer to them. However, in all cases it appears that the level of occupants' understanding of the purpose of the measures and systems is not significantly influenced by whether these are performed or installed properly; at the same time their performance and installation aspects have affected occupants' opinion and level of control over low-carbon improvements.

In the majority of cases (8 of 9) occupants' overall satisfaction was negatively affected by two main factors: the levels of training and the level of control actually provided over the measures. The training and information they received from the local authority, housing association or project team was generally very poor and most of the time insufficient. The training was focussed mainly on basic heating system controls like how to switch them ON/OFF, set up the timer and programmer and set more or less heat using the intelligent control panels, but did not include any information on other systems' controls (e.g. MVHR, solar panels, etc.). In terms of time the hand-out and information in all cases was generally provided after the completion of the works, and in 2 of 9 cases was delayed up to 7 months despite 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)

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. Often the person involved in the demonstration was someone from the local authority or house association who did not always have technical expertise to introduce and train occupants on the specific measure. The type of information varied in the sample from a quick demonstration to a single page leaflet or a booklet with very broad information on energy issues, but not always on the controls of the measures installed. Occupants' interest in measures' controls was constrained significantly by the type of instruction, as often they were left out of technical specifications manuals for installation and maintenance and many were not even in English:

> [Training/instructions provided] … no, none at all … they were coming [builders/technicians] doing a work and then leaving, whereas the housing association didn't knew 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)

Very little to no information was provided to the households about the passive (operation of windows and doors) and active (MVHR system) ventilation and how mechanical system performance and air quality in the room can be affected by their actions. As reported in the interviews the only instruction that the occupants were given was 'not to open the windows:'

> … they said we are not supposed to open them [windows] … only in the summer … (Occ. TSB047)

The information and training provided to the occupants in the sample is a different type of 'knowledge' from what was generally involved in previous practice theory considerations (Gram-Hanssen 2010; Reckwitz 2002; Shove and Pantzar 2005). In this sample occupants' knowledge is highly related to their engagement with the process as part of the RfF competition programme. Except for the RfF information/training provided on the measures occupants' knowledge involves transfer of knowledge from previous interactions with similar systems or practices. In the majority of cases the level of knowledge of energy efficiency issues derives mainly from their personal proactivity and interest in energy matters together with their individual engagement to interact with low-carbon controls. The person and the type of information/training (from a leaflet to an in-situ demonstration) are viewed in these cases as the instruments that contribute to occupants' engagement, affecting knowledge and to some extent their control practices.

Financial concerns in the post-retrofitted stage were among the main motivations that engaged occupants with the new measures and fostered behaviour changes so that they can cost benefited by the RfF property. More than half of the occupants in the sample when talking about their energy behaviour change describe themselves as being quite 'environmentally conscious' before the low-carbon works. Their statements mainly involve broader views of green lifestyles (recycling), controls over electricity (switching OFF the lights and putting appliances on standby) and awareness of their energy bills. Their personal views on energy awareness differ in the sample. In 6 of 9 cases they believe that the refurbishment has raised their consciousness and made them more aware and enthusiastic about energy issues, whilst others talk about no behavioural changes but highlight their great expectations of reduced fuel costs from the low-carbon interventions. This latter point was indeed an expectation of all occupants in the sample. Therefore, while some occupants relied merely on systems and measures for lower bills, for others this has been a significant motivational lever for changing their practices. However, the fact that in 8 out of 9 cases their bills[2] have increased rather than decreased has left occupants with a mixed understanding of the impact their practices and behaviour change have. Additionally those occupants with PV panels installed had very unclear information and low awareness as regards the amount of electricity they generate, and whether it is offset from their bills or benefitted by the measure at all. For some their personal explanation of these bills rise was not related to their practices no behaviour change, but to the MVHR system and the lack of control they have to switch it OFF when not at home. Such aspects involved in occupants' behaviour change in the post-refurbished building environment have been viewed in this paper through the lens of behavioural and psychological adaptation approaches (Liu et al. 2012). These highlight that occupants' adaptation is influenced by multiple correlated factors like climate, economics and culture and by occupants' perceptions and reactions to information, like energy costs in this case, due to their subjective past and-post experiences.

#### Thermal comfort and occupants' adaptations

Regarding their comfort, the occupants have made physiological and behavioural adaptations directly related to both heating and ventilation actions. Adaptive thermal comfort theoretical approaches revealed physiological parameters in the sample related to the occupant's health status, age or gender. These are correlated to different comfort levels between occupants and frequently to personalised temperatures in the rooms based on their individual comfort preferences. Therefore, for instance in case 81 the male particularly feels the cold when under medication, while the female feels too hot due to menopause effects. In more than half of the cases in the sample (5 of 9 cases), occupants' heating post-experience and comfort satisfaction in the refurbished property is largely constrained by malfunctioning of the system or heating controls. In this respect in properties like TSB100 it was difficult for the occupants to define their comfort levels:

> [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).

In all properties occupants' 'sayings' were triangulated with their 'doings' using spot measurements carried out the same day as the interview and the one year monitoring data (Table 4).

Despite occupants' comfort differences within each household all interviewees seem to have a good understanding of their comfort levels and generally their sayings do not have significant divergence from the spot and monitoring measurements. The mean internal temperature between floors varies in the sample from 0.2 °C to a maximum of 2.7 °C. In a highly occupied house (24 h/day and 7 days/week) like in case TSB036, occupants are aware of the 2–3 °C difference between their comfort level and indoor temperature, which for them, especially on the 1st floor, often is uncomfortably warm. Their intention to decrease the temperature of the heat pump boiler (now set at 20 °C) is delayed/constrained by the inflexibility of the heating control system (Wattbox). Comfort adaptation for occupants like in case TSB054 is related to past experiences that made them conscious of adding an extra layer of clothes when this is required instead of turning up the heating. The post-experience for others when Wattbox was a barrier in regulating heating like in case TSB033 and 036 is switching ON ventilation fans or opening windows as their common practice to lower room temperature. The level of control and means the occupants use to balance their comfort preferences and overall indoor temperature are discussed thoroughly in the following section.

#### Heat controls and occupants' doings and sayings

In most of the cases (6 of 9 cases) there are no differences between occupants in operating heating controls and their level of interaction with the measure is similar. Occupants' adaptive behaviour is highly related to the 'open'/'closed' scripted system controls that were provided/installed. Therefore, for those cases

2. This involves electricity bills up to the day of the interviews.

**Table 4. Variations in occupants' doings and sayings in relation to their comfort level and indoor temperatures.**

| In-situ measurements | | | | Sayings | Doings | |
|---|---|---|---|---|---|---|
| Cases TSB id | Collection Day | Ext. Temp. ºC | Heating ON/OFF | Occupant's Comfort ºC | Mean Temp. Ground Floor ºC | Mean Temp. 1st Floor ºC |
| 034 | 06 Sept 2011 | 16 | OFF* | 19–21 | 19.0 | 20.0 |
| 007 | 26 Jan 2012 | 8 | ON | 22–24 | 20.7 | 22.8 |
| 036 | 08 Sept 2011 | 16 | ON | 20–21 | 23.2 | 24.1 |
| 054 | 07 Sept 2011 | 14 | OFF | 18–22 | 22.1 | 21.8 |
| 033 | 06 Jan 2012 | 1 | OFF* | 20–21 | 20.0 | 22.7 |
| 076 | 03 Feb 2012 | 12 | ON | 21–25 | 21.1 | 22.7 |
| 100 | 11 Oct 2011 | 9 | OFF* | 19–20 | 18.5 | 18.0 |
| 05 | 08 Feb 2011 | 10 | ON | 21 | 20.0 | 21.4 |
| 072 | 09 Mar 2012 | 10 | ON | 20–21 | 20.2 | 20.4 |

** OFF because the heating system was broken on the day of the interview.*

with the CHP and heat pump boilers, occupants' direct interaction with boiler controls is generally passive as initially scripted from the measure. However, occupants report the factors that make them passive with this type of controls is not entirely 'closed' by the measure but also by the type of instructions they received (told 'not to touch'), as well as by individual behaviour factors as they feel discouraged and 'afraid' to have interaction with such a complicated and expensive piece of equipment. Nonetheless, in cases TSB88 and 05, when occupants were left with no control over the CHP system and with no heating and hot water their behavioural constraints were overtaken by taking control (action) over the CHP boiler from unit controls by rebooting it.

Occupants' level of interaction in terms of usage is strongly related and compared in their sayings to their previous experience with controls. Therefore, although they found indirect interaction with heating controls to be simple, as with the intelligent system Wattbox or Optima Design Controller, they are generally dissatisfied with the level of actual control this gives them over heating when compared to their past-experience. In some properties (cases TSB036, 034, 100, 033, 047 and 076) occupants believe that the intelligent heating controls are prefigured by the measure installation and not working properly. This in some instances is found to be right as the Wattbox often was not communicating properly, especially with systems like CHP boilers. One of the major issues identified in occupants' interaction with the intelligent system controls was that heating control was scripted and would not allow them to instantaneously make changes to their comfort preferences:

> … even if we use the Wattbox, which is the official way of up and down temperature, it takes about a couple of days to react … so it's not if I am hot I am going to turn the thing down but what if tomorrow it's freezing cold and I want it up again … so it's better to adjust those things [comfort levels] by open the windows … (Occ. TSB036)

This issue was also related to Wattbox's scripted options to occupancy limiting occupants' comfort adaptivity and controls. Therefore in cases TSB100 and 034, where the house is not occupied during the day, Wattbox controls become a limitation as Wattbox needs a couple of days 'to learn' and adjust to occupants' settings. As an occupant from case TSB033 explains:

> … they said if you find it a bit cold is like a learning thing [Wattbox] it learns if you adjust it … it's like a learning computer … (Occ.TSB033)

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, having a mixed to poor level interaction.

Other types of interaction with heating controls related to occupants' past-experience and know-how relate to the gas boiler controls. This type of interaction control varies in the sample. For instance, occupants in case TSB81 have full interaction as they find it simple to set up the programmer and arrange their preferences regarding occupancy times and temperature comfort levels. In contrast, in cases TSB072 and 076 they have no interaction with the programmer settings and only manual control over it, but they are active with the thermostat controls (good/full interaction) using the same practices they used with these controls in the post-works experience.

Another control strongly related to occupants' past-experience and practices to regulate room temperature is through TRVs. In the majority of cases occupants have good control over radiators' TRVs whereas their adaptive behaviour is not 'scripted' by the measure, allowing the frequency of their interaction to be only comfort and season dependent. Generally, the TRV control settings vary between rooms and floors depending on occupants' comfort temperature preferences for the specific room and on the level of awareness and engagement over energy conservation, keeping for instance radiators OFF in the non-occupied rooms. In two cases in the sample users' mixed/passive interaction with the TRV controls is due to the design strategy (case TSB036 TRV controls are only in bedrooms) and to the level of information/training provided (insufficient information for the remote controlled TRVs). The triangulation of the physical measurements confirms occupants' statements about turning OFF/ON the space heating, showing that most of them – when it is not scripted by the measure – consciously regulate and operate heating system controls.

Operation of openings, although traditionally related to ventilation controls, has a significant effect on heating comfort. The interactions identified in door control show that occupants in more than half of the cases tend to be active with door operation, due more to privacy factors than to heat conservation in the rooms. In the rest of the cases occupants often keep the doors open in all rooms – heated or non-heated and even in those not used – due to psychological and behavioural factors or to occupants' age (e.g. young children, teenagers). A different example that prescribes users' comfort controls and psychological adaptation, determining the level of their 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. No particular frequency of interaction was found in the use of doors, except the kitchen door due to cooking practices.

However, there is a significant behavioural change in most of the cases (5 of 9 cases) 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 occupants to open any of the windows in the house, as:

> it was so cold that we couldn't actually leave any window open (Occ. TSB054).

But then again even in the post-retrofitted environment some of the occupants (cases TSB036, 007, 054, 047 and 076) show past-experience habits by opening windows routinely, even in the winter, and regulate their comfort levels by consciously leaving, for instance, some bedrooms' windows slightly open all the time, even overnight. In some cases there is a significant behavioural change explained as a cultural issue: "… it's how I grew up" (occ. case TSB054); the individual explains her cultural values and routinised habits by trying to associate them with other conditions and rationalise them to herself. The frequency of window controls varies throughout the house depending on the activity that takes place in the room. Therefore, in practices of cooking or bathing all occupants tend to have the windows open during or after their activities, whereas in the living and sleeping areas windows are opened for a certain time for airing. Other factors found to affect and prescribe windows control and operation are the design and technology of the product, discussed in the following section.

#### Air quality comfort conditions and ventilation controls

The air quality of the indoor environment is provided through passive ventilation by opening doors and windows and by active ventilation via MVHR installed in all rooms. As discussed above, in the majority of the cases occupants overall have full control over the passive ventilation measures by opening and shutting windows and doors according to their comfort preferences. Comfort adaptation and controls in all properties follow climatic 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. Some of these occupants (cases TSB033 and 036) prefer to have the electric fans ON. Another significant factor found to affect occupants' interaction was the level of design participation[3] and choice they had over the improvements. Therefore in properties like cases TSB036, 072 and 034, openings' design and installation had a significant impact on how they 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. For instance in cases like TSB034, 047, 033, 036 and 072 the increased width of the wall (insulation standards), the window's outward opening direction and the distance from the kitchen sink are design aspects that significantly constrain the occupant from reaching and having control over the kitchen window.

The active MVHR systems were designed to supply air to the long occupied rooms like living room, dining room and bedroom, and exhaust the air from the wet rooms like the kitchen and bathrooms. In 6 of 9 cases occupants have no interaction or poor interaction with MVHR controls. Even in cases when control is provided often full operation is scripted by the measure (e.g. filter type, control panel options). As regards the impact of the MVHR system on the overall indoor environment in the properties, there is generally an even distribution of air in all rooms whilst no particular issues were identified in maintaining comfort conditions throughout the house. However, in properties like cases 48a and 16, to regulate the uneven distribution and intensity of the blown air in some rooms, occupants had to interact with MVHR vents by closing them completely. Other controls like the booster fans in the wet rooms (kitchen and bathroom) were found insufficient in all cases for the steam and humidity levels from bathing and cooking practices; therefore opening windows even in the cold months has been a quite common event of interaction for most occupants. Other factors like noise from the MVHR system are now attenuated by behavioural adaptation, with the female in case TSB054 saying 'now, I get used to it'. Occupants' experience and perceptions with the MVHR system vary in the sample. On one hand they are often related to air quality comfort, with an occupant reporting that the air feels different and much nicer (case TSB054). Other occupants are indifferent (case TSB072) or report negative change to their adaptive comfort compared to past-experiences:

> in the summer it was pretty uncomfortable … it was so hot in the metre it was showing 27 °C … it made me feel sick … you can open the window but I've been told not to … in the end that day I opened them (windows) (Occ. TSB034)

On the other hand most commonly expressed is a general concern about increased electricity bills:

> … if we turned it OFF [MVHR system] … it would be nice to see how much electricity it saves … cause I reckon it uses quite a bit … (Occ. TSB007).

3. In this sample household participation was limited to minor aesthetic aspects (e.g. wall colour, floor finishes) and only for those cases in which health issues were involved were occupants' preferences considered in the design.

For those dissatisfied occupants the only reason for not turning the MVHR system OFF was either the lack of control over the central unit in the loft or their engagement with the RfF monitoring process.

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. In all cases occupants' understanding was generally mixed on how to operate windows and MVHR system in warmer and cooler months; to some extent this was related to the mixed information/training they had for the new measure. The instructions they received from the project team were reported as 'don't need to touch it', which has prevent 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 $CO_2$ levels.

The empirical data was cross-checked with the physical measurements to explain the impact of the system on occupants' comfort. The in-situ measurements of $CO_2$ levels in all actively occupied rooms compared to the CIBSE indicators[4] for adequate air quality (CIBSE 2005) showed $CO_2$ level variations between floors. In 5 of 9 cases $CO_2$ levels are at adequate levels while in the rest they either fluctuate between floors from normal to poor or are poor on both floors. There are properties like cases 81 and 05 in which $CO_2$ levels are especially high despite the main bedroom windows always remaining open throughout the day and the MVHR constantly ON. Such findings indicate the effect of factors like mal-operation due to installation, occupants' vents and opening control and micro-factors significantly affecting the performance of the measure.

## Discussion and conclusions

Drawing on the analysis of the empirical data above, key factors affecting occupants' interaction emerged. Occupants' past-experience in a poor building environment had a significant impact not only on their comfort levels and awareness of energy cost but also their routinised practices related to heating/ventilation controls. Interactive effects at the pre-retrofit stage were largely scripted by the technology and products and were directly prefigured by the physical condition of the building fabric, systems' age/type and heating expenses. These factors have determined to a great extent occupants' physiological and behavioural adaptation and made them passive recipients with merely a few controls.

The post-retrofit environment 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. Therefore, there are cases in the sample where buildings' airtight environment allows occupants to choose their habits and adapt their routines in a more impulsive way compared to their past-experience, especially in the way they operate openings. The low-carbon technology of the building fabric, systems and measures affects occupants' controls 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. Therefore, in heating practices such issues allow some of the occupants to be active users dealing with an active heating system that responds to their controls and heating practices supporting their physiological and behavioural preferences. 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 (Table 5).

Another important factor in occupants' post-experience control related behaviour in heating/ventilation practices is knowledge. There are three types of knowledge in 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. Therefore in some cases the know-how of regulating heating controls like the TRV valves or the thermostat and programmer involves a transfer of knowledge from past experiences of interaction with similar technology, whereas occupants' interaction with Wattbox controls or MVHR builds 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 please' of 'doing the right thing' and contrasts with routinised practices, in this case leaving the windows open or block the filter vents. This highlights 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 (heating vs. ventilation, active vs. passive).

With regard to heating, occupants are active users both directly and indirectly 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 an 'as designed' active measure. In passive ventilation occupants have full control and active interaction through openings when design faults are not involved, although not with a positive effect on the mechanical ventilation system. The active ventilation was installed and explained to all occupants as a passive measure; however, occupants have an indirect influence over it as active users by interacting with openings. 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 which practices and measures affect each other and often a mixed interaction not as designed.

From the discussion above it is clear that overall active measures as designed and installed have fostered direct interaction involving active users, whilst the passive low-carbon measures designed and installed for passive users tend to involve indirect interactions with active users. Occupants' knowledge transfers from previous heating comfort practices and controls or issues of installation failures have been compromised to some extent by the post-experience of living in a

4. CIBSE carbon dioxide ($CO_2$) indicator for adequate air quality: 800–1,000 ppm for adequate air quality.

Table 5. Scripted (or not) controls of systems and measures in-use (n=9 buildings).

**Systems and measures in-use**

| System operated… | | Directly/ Indirectly | Via measures | Controls for… | *Interaction with the measure (% of cases in the sample)* |
|---|---|---|---|---|---|
| Heating | | | | | |
| *Space* | Gas Boiler | ***D:*** | Gas boiler controls | ***Act*** *users (33%)* | *22% Act, 11% Pass* |
| | | | CHP boiler controls | ***Pass*** *users (33%)* | *33% Pass* |
| | micro-CHP | | Heat pump boiler controls | ***Pass*** *users (44%)* | *44% Pass* |
| | | | Thermostat | ***Act*** *users (33%)* | *33% Act* |
| | Heat pumps | | Programmer | ***Act*** *users (33%)* | *22% Act, 11% Act/Pass* |
| | | | TRVs | ***Act/Pass*** *users (88%)* | *44% Act, 22% Act/Pass, 22% Pass* |
| | | ***I:*** | Intelligent control systems | ***Act*** *users (66%)* | *33% Act/Pass, 33% Pass* |
| | | | MVHR fan controls | ***Act*** *users (11%)* | *11% Act/Pass* |
| *Hot water* | Gas boiler | ***D:*** | Gas boiler controls | ***Act*** *users (33%)* | *33% Pass* |
| | micro-CHP | | CHP boiler controls | ***Pass*** *users (33%)* | *33% Pass* |
| | Heat pumps | | Heat pump boiler controls | ***Pass*** *users (44%)* | *44% Pass* |
| | | | Solar thermal controls | ***Pass*** *users (44%* | *44% Pass* |
| | Solar thermal | ***I:*** | Programmer | ***Act*** *users (33%)* | *22% Act, 11% Pass* |
| | | | Intelligent control systems | ***Act*** *users (66%)* | *22% Act, 44% Pass* |
| Ventilation | | | | | |
| *Passive* | Windows | ***D:*** | Window operation | ***Act*** *users (88%)* | *33% Act, 33% Act/Pass, 22% Pass* |
| | | | Windows' filter vents | ***Act*** *users (11%)* | *11% Pass* |
| | Doors | ***I:*** | Door operation | ***Act*** *users (88%)* | *22% Act, 22% Act/Pass, 44%Pass* |
| *Active* | MVHR | ***D:*** | MVHR controls | ***Pass*** *users (11%)* | *11% Pass* |
| | | | Control panel | ***Act*** *users (33%)* | *11% Act, 22% Pass* |
| | | | Boost button | ***Act/Pass*** *users (44%)* | *33% Act/Pass* |
| | | | Filter controls | ***Act*** *users (66%)* | *22% Act, 44% Pass* |
| | Electric fans | | Fans ON/OFF | ***Act*** *users (22%)* | *22% Act* |
| | | ***I:*** | Opening operation | ***Pass*** *users (88%)* | *88% Act /Pass* |

*D = Directly, I = Indirectly, Act = Active, Pass = Passive.*

satisfactory indoor environment overwhelmed by forgiveness and forget factors. Occupants' personal interest and proactivity in some cases 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 cause inefficiency. Apparently this had an influence on households' interactions and routinised practices. Interactions associated with the control of indoor temperature were mostly engaged with practices of sleeping, relaxation and entertainment, whereas ventilation controls were more engaged with practices of cooking, bathing and cleaning. Concerning the frequency of occupants' interactions, to a great extent these have occurred with routinised regularity and often with seasonal dependency.

Overall in some cases the failure of the operating controls in-use as scripted is mainly due to interrelated factors like installation faults of combined systems and operational limitations due to the design and installation of products. The poor type of information and often lack of expertise to demonstrate controls to the users also contributed to passive users and interactions. The new economic dynamics and expectations from fuel bills, occupants' understanding of the new measures controls and the level of awareness of energy matters also affect the level of occupants' passive/active interaction in the low-carbon properties. In most of the households in this sample the lower than expected reduction of bills has not been achieved.

## References

Akrich, M. (1992), 'The de-scription of techical objects', in W E. Bijker and J. Law (eds.), *Shaping technology/building society: studies in sociotechnical change* (Cambridge: Mass.: MIT Press), 205–24.

Bluyssen, P. M. (2009), *The Indoor Environment Handbook: How to Make Buildings Healthy and Comfortable* (London: Earthscan Ltd).

CIBSE (2005), 'Guide B: Heating, Ventilating, Air Conditioning and Refrigeration. ', (London: The Chartered Institution of Building Services Engineers).

Cramer, James C., et al. (1984), 'Structural-behavioral determinants of residential energy use: Summer electricity use in Davis', *Energy,* 9 (3), 207–16.

Gram-Hanssen, K. (2009), 'Standby consumption in households analyzed with a practice theory approach', *Journal of Industrial Ecology,* 14 (1), 150–65.

— (2010), 'Residential heat comfort practices: Understanding users', *Building Research and Information,* 38 (2), 175–86.

Hitchcock, Guy (1993), 'An integrated framework for energy use and behaviour in the domestic sector', *Energy and Buildings,* 20 (2), 151–57.

— (1995), 'The human dimension of domestic energy use: An Integrated Approach', (Faculty of Technology The Open University UK).

HM Government (2008), 'Climate Change Act 2008', (The Stationery Office Limited, London, UK).
Jenkins D.P. (2010), 'The value of retrofitting carbon-saving measures into fuel poor social housing', *Energy Policy,* 38, 832–39.
Liu, Jing, Yao, Runming, and McCloy, Rachel (2012), 'A method to weight three categories of adaptive thermal comfort', *Energy and Buildings,* 47 (0), 312–20.
Lomas, K, Summerfield, A, and al, et (2006), 'COBRA: Understanding the Social and Technical Factors that Influence Energy Use in UK Homes.', in Carbon Reduction in Buildings (CaRB) (ed.).
Lutzenhiser, L and Bender, S (2008), 'The 'average American' unmasked: social structure and differences in household energy use and carbon emissions', *ACEEE.*
Nicol, J. F. and Humphreys, M. A. (2002), 'Adaptive thermal comfort and sustainable thermal standards for buildings', *Energy and Buildings,* 34 (6), 563–72.
Reckwitz, A. (2002), 'Toward a Theory of Social Practices: A Development in Culturalist Theorizing', *European Journal of Social Theory,* 5 (2), 243–63.
Shove, E. (2003), 'Users, technologies and expectations of comfort, cleanliness and convenience', *Innovation,* 16 (2), 193–206.
Shove, E. and Pantzar, M. (2005), 'Consumers, producers and practices: Understanding the invention and reinvention of Nordic walking', *Journal of Consumer Culture,* 5 (1), 43–64.
Topouzi, M. (2011), 'Understanding occupants' interaction with the technical change in low-carbon retrofits: A methodological and conceptual framework', *Proceedings of ECEEE Summer Study, 6–11 June, 2011* (Belambra Presqu'ile de Giens, France).
Vischer, J. C. (2008), 'Towards a user-centred theory of the built environment', *Building Research and Information,* 36 (3), 231–40.
Yao, R and Steemers, K (2005), 'A method of formulating energy load profile for domestic buildings in the UK', *Energy and Buildings* (37), 663–71.

## Acknowledgements

The author would like to thank Dr Nick Eyre and Dr Rajat Gupta for their guidance, revision and support in this research. Thanks should also go to the Technology Strategy Board and Retrofit for the Future programme for providing the data as well as to the UKERC/NERC for giving me this research opportunity.