Low/zero energy social housing in UK: a case of under-performance or unintended consequences?

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Keywords

low-energy house, energy performance, user behaviour, monitoring, zero-carbon technologies

Abstract

This paper investigates the actual performance and unintended consequences on energy use and environmental conditions of six case study dwellings in three new 'low/zero' energy social housing developments in UK, through building performance evaluation techniques comprising: remote monitoring of energy use, end-use demand, environmental conditions and window-opening behaviour, cross-related with forensic data on building fabric and systems' performance as well as qualitative data gathered through occupants' surveys and interviews, review of control interfaces and handover guidance. Actual performance is measured for mechanical ventilation systems (with heat recovery [MVHR]) and electricity-generating technologies (solar photovoltaics). The case study houses cover a variety of built forms (end terrace, mid terrace, detached) and construction systems (hempcrete, lightweight steel-frame with pre-insulated panels, and conventional timber frame and brick), but tend to have similar occupancy profiles.

Despite all the developments being designed to high energy standards, the actual energy use exceeds design expectations by a factor of three, questioning the need for whole-house MVHR systems at measured air permeability rates of 6 $m^3/(h.m^2)$ against the design target of 3 $m^3/(h.m^2)$. Lack of proper commissioning of MVHR and heating systems, combined with inadequate user comprehension about their operation and control due to poor guidance during handover, leads to occupant 'misuse' wherein systems are de-activated, thereby negatively affecting indoor air quality. A series of unintended consequences occur, such as higher demand temperatures set by occupants, unexpected opening of windows during winters due to under-performance of MVHR combined with habitual behaviours, over-use of heating systems to compensate for higher than expected air permeability, thereby increasing the gap between designed and actual performance. For low/zero houses to perform as intended it is important to tackle these inter-dependencies between building, technology and occupants right from the design stage through to construction, handover and operation.

Introduction

In the UK, like other European countries, about 27 % of all carbon dioxide (CO_2) emissions are related to energy use in housing (DCLG, 2009). The housing market has seen an exponential development of policy culminating in energy certificates, in line with the EU Energy Performance of Building Directive (EU, 2010), the Code for Sustainable Homes (CSH) assessment, and a series of other regulations aiming to improve the energy performance of houses and reduce their carbon emissions. The Government has set ambitious targets for incremental changes to building regulatory standards, which are intended to achieve 'zero' carbon new housing from 2016 onwards (UKGBC, 2008) by the implementation of sustainable design principles and micro-generation technologies.

Despite this driver, many low carbon solutions are untested, creating a gap between 'expected' (modelled) and 'in-use' (measured or actual) energy performance. The result is that even new low carbon housing is using between three-five times the energy predicted by models (Monahan and Gemmell, 2011; Thompson and Bootland, 2011). Although research has revealed that the physical building characteristics, performance of systems and occupant behaviour all play a significant role in determining actual energy use in buildings (Sharpe and Shearer, 2013; Gupta et al., 2013), the reasons for the gap between predicted and actual performance are not precisely understood. Concern is also growing in the UK that this performance gap found in typical mainstream home production has the potential to undermine zero carbon housing policy and carry considerable commercial risk for the wider industrial sector (Zero Carbon Hub, 2013). Evaluating the actual building performance of housing, taking account also of the relationship with user behaviour, can help establish some of the reasons for this gap and help to bridge it by suggesting design improvements related to these (Stevenson and Rijal, 2010; Zero carbon Hub, 2013).

Furthermore, with new housing in the UK experiencing rapidly changing standards, leading to innovations in materials, technologies and construction, it could be argued that all new domestic buildings are some form of experiment whose performance needs to be systematically evaluated to learn lessons in order to make the required changes to improve future designs (Sharpe and Shearer, 2013). However little real feedback exists on how housing is performing during occupation, which makes it difficult to ascertain whether targets are being achieved in reality, whether the design, procurement, and management strategies are actually working and whether occupants are actually reducing their demands and expectations. The effectiveness of occupant feedback in clarifying why a technology does or does not work has been highlighted in several studies (Firth et al, 2008). An interdisciplinary approach has been suggested for identifying the unintended consequences derived from the implementation of new technologies and construction methods (Davies and Oreszczyn, 2012). However, limited studies have been undertaken in the housing sector for measuring actual fabric performance and reviewing the commissioning of services and systems (Wingfield et al, 2011; Gupta et al, 2013), as well as understanding the influence of occupant behaviour and interaction with technology.

This study investigates the actual energy use and environmental conditions of six case study dwellings in three new 'low/zero' energy social housing developments in the UK, using the mixed-methods empirical approach of Building performance evaluation (BPE). Quantitative and qualitative findings are cross related to understand the reasons for the underperformance of services and systems, as well as unintended consequences that affect energy use, indoor environmental conditions and air quality due to underperformance of building fabric, services and systems, as well as occupant behaviour. Wider lessons for the industry are extracted and recommendations are made to reduce the gap between intent and actual performance.

Methodology-Building Performance Evaluation as a method for evaluating housing performance

BPE is the process of evaluating the performance of a building through a systematic collection and analysis of qualitative and quantitative data related to energy performance, environmental conditions and occupant feedback. BPE involves feedback and evaluation reviews at every phase of the building delivery from strategic planning to occupancy, adaptive reuse and recycling (Preiser and Visher, 2005). In recent years, several methods have been developed to capture co-incident data from monitoring and occupants (Stevenson and Rijal, 2010).

The UK Government's innovation agency, Technology Strategy Board (TSB) (now Innovate UK) has funded an £8 million, 4-year national research programme that aims to undertake studies and develop capacity for BPE for both domestic and non-domestic buildings across the UK, so as to help the construction industry deliver more efficient, better performing buildings (TSB, 2012). The programme mandates a prescribed protocol for evaluation and reporting, to maintain consistency and comparability in benchmarking and analysis. Studies include Phase I projects, which undertake post-construction testing and early occupancy, and Phase II studies, which additionally undertake monitoring of energy and environmental conditions for a 24-month period.

This paper presents data and findings from three BPE projects (one Phase I and two Phase II projects) studies by the Low Carbon Building Research Group[1]. The LCB group, within which the authors are based, has been involved in evaluating the energy and environmental performance of six low-carbon case study dwellings by capturing co-incident data on energy use and in-situ environmental conditions including air quality (temperature, relative humidity (RH) and CO_2 levels) as well as opening and closing of doors and windows, collected between January 2013 and December 2013 (12 months). This co-incident data is collected every five minutes from wireless sensors that monitor temperature, RH and CO_2 and is transmitted wirelessly from a RT:Wi5 data-hub. This physical data is cross related with qualitative data gathered through occupant satisfaction surveys and interviews, supplemented by occupant self-completion activity logging and thermal comfort diaries across different seasons. Fabric performance is evaluated using diagnostic field tests (U-value tests, air-permeability tests and thermographic surveys) along with a review of the installation and commissioning of services and systems. The communication of design intent to users is evaluated by observing the handover process and assessing the home user guides. Usability is assessed through a detailed qualitative review of control interfaces that occupants interact with.

Overview of case studies

The six case study dwellings are part of three exemplar social housing developments (A, B and C) located in South-East England. All developments were completed between 2011 and 2012: Case A has been occupied since March 2011, Case B since August 2012 and Case C since March 2012. The six case studies (two per development – A1, A2, B1, B2, C1 and C2) were selected to represent a variety of built forms and construction systems. The case study houses are two and three storey mid-terrace, end-terrace and detached houses of two, three and five bedrooms, located in residential areas. The size of the properties varies, the smallest being 94 m^2 and the largest being 146 m^2. The layout of the houses is similar (with the living areas on the ground floor and sleeping areas on the upper floors), with the exception that Case A houses have an open plan layout on the ground floor. Cases A1, A2, C1 and C2 were monitored for a

1. The LCB group undertaking the study was independent of the building and design teams. The group was responsible for collecting and analysing the data.

period of two years and Cases B1 and B2 were monitored for a period of one year. Table 1 presents an overview of the design specifications and construction details of the case studies, while Table 2 shows their background characteristics.

Development A was designed for Code for Sustainable Homes (CSH) Level 5 and Developments B and C were designed for CSH Level 4. Different types of construction were used in the three developments ranging from hempcrete in Development A to light-weight steel frame construction with pre-insulated panels in Development B and more traditional timber frame with brick in Development C. Additionally, each of the developments features a different heating system; from Exhaust Air Heat Pumps (EAHP) in Development A to Air Source Heat Pumps (ASHP) in Development B and gas boilers in Development C. Designed for air permeability of 2–3 m^3/m^2h, all case study dwellings have whole house mechanical ventilation with heat recovery systems (MVHR) along with windows that can be manually opened and closed. All six dwellings also have solar photovoltaic systems to provide electricity, and all but dwellings C1 and C2 are electrically heated. All of the six case study houses are occupied by families with children (Table 2). The number of occupants is high, ranging from 4 people (2 adults and 2 children below the age of 12 in Cases A1, A2 and B1), 5 people (4 adults and 1 baby in Case B2, 2 adults and 3 children in Case C1) and 6 people (1 adult and 5 children below the age of 16 in Case C2). Cases A1, A2 and B2 are occupied 24 hours/7 days a week, and Cases B1, C1 and C2 are occupied 17–19 hours during weekdays and 24 hours during weekends.

Unintended consequences affecting performance

COMMUNICATION OF DESIGN INTENT: EVALUATION OF HANDOVER, TRAINING AND GUIDANCE

In order to identify any unintended consequences of occupant behaviour on housing performance, it is essential to capture the actual process by which the occupants develop their own understanding of how to use the home (Stevenson and Rijal, 2010). The formal introduction to the home is the first critical interface between the inhabitant (occupant) and their interaction with the building. The handover process (home introduction and training) and guidance (home user guide, technical manuals) that occupants receive before and after moving into their new home was carefully evaluated in terms of clarity, communication and user engagement. The findings are triangulated with the occupants' answers to interview questions about the effectiveness of the handover process, to gain deeper insight into occupants' understanding of the systems and to establish whether the documentation that occupants received was sufficient in communicating the design intent and operation of the new home without being overly technical or confus-

Table 1. Design specifications and construction details of case study dwellings.

	Development A	Development B	Development C
Developer	Social housing/Local authority		
Tenure	Affordable housing rented		
Completion date	March 2011	August 2012	March 2012
Area (m^2)	94	94	88
Typology	Two bed, mid-terrace	Two bed, mid-terrace	Three bed, end-terrace
Floors	2	2	2
Construction type	Timber frame with cast hempcrete	Steel frame with pre-insulated panels	Timber frame and brick
Target design rating	CSH Level 5	CSH Level 4	CSH Level 4
Main construction elements (as designed) U-values W/m^2K	Walls U-value: 0.18 Roof U-value 0.15 Floor U-value 0.2 Windows: double glazing, U-value 1.4	Walls U-value: 0.15 Roof U-value: 0.15 Floor U-value: 0.15 Windows: triple glazing, U-value ≤1.2	Walls U-value 0.21 Roof U-value 0.13 Floor U-value 0.25 Windows: double glazing, U-value 1.3
Space heating and hot water system	Exhaust Air Heat Pump (EAHP), underfloor heating and solar collectors	Air Source Heat Pump (ASHP), underfloor heating coils, immersion heater back up	Gas condensing boiler with radiators
Target air permeability (m^3/hm^2 @50Pa)	2	3	3
Ventilation strategy	Whole house MVHR through EAHP	Whole house MVHR	Whole house MVHR
Renewables	4 kWpk Photovoltaics	1.5 kWpk Photovoltaics	1.65 kWp & 1.88 kWp Photovoltaics

Table 2. Occupancy characteristics of case study dwellings.

	Development A		Development B		Development C	
No of case study houses	2		2		2	
Case study reference	Case A1	Case A2	Case B1	Case B2	Case C1	Case C2
Occupancy patterns	Weekdays: 24 h Weekend: 24 h		Weekdays: 15:00–8:00 Weekend: 24 h	Weekdays: 24 h Weekend: 24 h	Weekdays: 13:00–8:00 Weekend: 24 h	
Occupants	2 adults, 2 children	2 adults, 2 children	2 adults, 2 children	4 adults, 1 baby	2 adults, 3 children	1 adult, 5 children

Table 3. Common emerging issues highlighted by the review of handover and user guidance.

	Development A	Development B	Development C
No phased approach followed during handover			×
Handover would have benefited by follow-up sessions at least in summer and winter	×	×	×
Handover/induction/training did not let occupants try out systems and controls	×	×	×
Home user guide should be more simple and clear	×	×	
Home user guide was missing information on technologies installed in the house	×	×	
Home user guide could be shorter and more straightforward	×	×	×

ing. To achieve this, the housing association's (HA's) occupant handover process, which took place before occupants moved in the properties, was directly observed (providing rich feedback that was relatively quick to capture), with a member of the evaluation team shadowing a typical user introduction to the equipment and functioning of the home by HA's representative. Table 3 summarises the common issues that were highlighted by the handover observation and review of guidance offered to the occupants. Most of these issues are prevalent across the three developments.

Since the housing associations (as social landlords) have experience of managing a large stock of tenanted properties, they are more successful in organising and delivering comprehensive and engaging handover, training sessions and guidance, when compared to the Local authority owned Development C. Although in developments A and B the handover demonstrations were phased (before move-in, one month after move-in, three months after move-in) and clear, the occupants were not given the opportunity to try the various systems and control features for themselves which might have aided their initial understanding of how to use them. In Development C, there was no phased approach to handover, with occupants expected to comprehend a large amount of technical information (related to exhaust air heat pumps and mechanical ventilation) on the day of the handover itself. The review of home user guides revealed that they are usually lengthy documents containing extensive technical details from manufacturers' manuals which are often poorly illustrated, and fail to provide simple and clear guidelines on how to make the best use of heating and ventilation systems (at least on a seasonal basis – summer and winter modes). This is partly the reason why occupants across all the three developments seem to have failed to fully understand and retain the purpose and operation of the heating (especially heat pumps and underfloor heating) and mechanical ventilation systems, or seem to have forgotten the information that was provided to them initially (Gupta and Kapsali, 2014) . Findings also suggest that not all occupants comprehend the training and guidance provided in the same way, suggesting that attention to any kind of training or guidance is also a matter of personal interest, as well as technical ability and age (BSRIA, 2014; Gupta and Kapsali, 2014).

USABILITY OF CONTROL INTERFACES

Control interfaces are the meeting point between users and building technology or fabric. The six-point criteria developed by Buildings Controls Industry Association (BCIA) were used to visually rate the performance and usability of control interfaces (Bordass et al, 2007) of heating, ventilation and lighting systems, as well as touch-points of the building fabric (window controls). These criteria include clarity of purpose, intuitive switching, usefulness of labelling and annotation, ease of use, indication of system response, degree of fine control as well as accessibility. Such investigations into the relationship between the design and usability of controls give an indication of their effect on occupant control and housing performance (Topouzi,

Table 4. Common issues highlighted by review of control interfaces.

	Development A	Development B	Development C
Conflicting control strategies	×	×	
Oversimplified control interfaces (no indication of system response, no labelling)	×		
Overcomplicated heating controls and zoning		×	
No indication of MVHR failure or maintenance	×	×	×
MVHR unit inaccessible, located in loft		×	×
Windows and doors offer good fine control		×	×

2013). Table 4 summarises the overall key issues that emerge as a result of the review and rating of control interfaces across the three developments.

Critical controls such as thermostats (for setting indoor temperatures for heating systems) were found to have poor ease of use and indication of system response in both Developments A and B, albeit for different reasons. In Development B the designer's intention to provide occupants with good levels of control resulted in an over-engineered solution of six to eight room thermostats and one master thermostat per house, as well as excessive thermal zones that confused the occupants and could not be commissioned properly. In Development A on the other hand, temperatures were not graphically indicated on the thermostat dials that only featured an arbitrary scale and showed no indication of system response. In the absence of clear annotation and numbering the users had to experiment to figure out which setting would offer comfortable temperatures. Such issues led to poor ease of use and lack of occupant understandings in both cases. This in turn affected occupants' ability to manage their comfort and resulted in increased heating energy use. Furthermore, controls and systems that are kept 'out of sight' were ignored by the occupants leading to poor maintenance (filter change) or even disuse.

Apart from issues with heating controls, provision of usable and well-located controls for the mechanical ventilation (MVHR) system was also a common issue for all case studies. In Cases A1 and A2 boost buttons are hidden in cupboards on the first floor but occupants in both houses were not aware of it. Occupants in Developments B and C were even unaware of the location of the MVHR units, which sat in the roof spaces that are narrow and difficult to access. As a result of this, the MVHR system in Case B2 had broken down without the occupants realising it. Furthermore, the position of the supply outlets of the MVHR system directly above the beds in Case B1 bedrooms caused great discomfort (due to cold draughts arising from system imbalance) to the occupants who decided to manually shut the supply terminals. Had this development been as airtight as originally specified, reducing the fresh-air supply could have put the occupants' health and well-being at risk. The findings related to MVHR system installation, location of outlet terminals and inaccessible controls are particularly concerning as the use of these systems is becoming wide-spread in new houses (Behar and Chiu, 2013). With such deficiencies in installation, commissioning and operation, the future take-up of these systems for their contribution to ventilation, occupant health and achieving energy reduction, may become questionable (ZCH, 2013; Gupta and Kapsali, 2014). Such issues reveal the need for establishing a clear and integrated systems and controls strategy early on in the design process, as also suggested by Soft Landings (BSRIA, 2014).

INFLUENCE OF OCCUPANT BEHAVIOUR ON INDOOR ENVIRONMENT

To gain deeper insights into unintended consequences it is important to understand how occupant behaviour influences housing performance by gathering direct verbal feedback on the perceptions and experiences of the occupants once they have lived in their homes for a while and have become familiar with them. This is done through self-completed occupant questionnaire surveys and a 45-minute, semi-structured interview-walkthrough. Occupant surveys were carried out in all three developments using the domestic version of standardised Building Use Survey (BUS[2]) questionnaire which assesses occupants' reported levels of comfort and satisfaction with the dwellings design and internal conditions (summer and winter), and also evaluates the degree to which occupants perceive their needs are being met by the building. Completed BUS questionnaires were collected from eight houses in Development A (~60 % response rate), sixteen houses in Development B (~70 % response rate), and eight houses in Development C (80 % response rate) giving an overall response rate of 70 %.

Following the occupant surveys, more detailed information on occupant views, satisfaction and concerns was gathered through semi-structured interviews and walkthroughs with the occupants of the six case study houses and triangulated with the findings from the BUS surveys. Table 5 summarizes the positive and negative occupant feedback relating to controls, comfort and satisfaction with space, that was collated from the BUS survey and occupant interview-walkthroughs. Most of the findings are consistent with the findings from the physical performance of the services and systems, as well as the review of handover and control interfaces.

Occupants are fairly satisfied with the appearance, design, layout and space of the houses across all three case study developments. Most negative feedback revolves around the op-

2. The BUS methodology is an established way of benchmarking levels of occupant satisfaction within buildings using a structured questionnaire where respondents rate various aspects of performance on a scale of 1–7.

Table 5. Issues revealed by occupant survey and qualitative interviews.

	Development A	Development B	Development C
Positive feedback			
Satisfaction with space and layout	×	×	×
Satisfaction with design and appearance	×	×	×
Satisfaction with light levels (natural, artificial)	×		×
Perceived overall internal temperatures good	×	×	×
Negative feedback			
Poor control over heating system	×	×	
Lack of understanding of operating heating system	×	×	
Lack of knowledge about MVHR system	×	×	×
Poor control over mechanical ventilation	×	×	×
Hot during summer		×	
Home User Guide considered complicated.	×	×	
Energy bills considered high	×	×	×

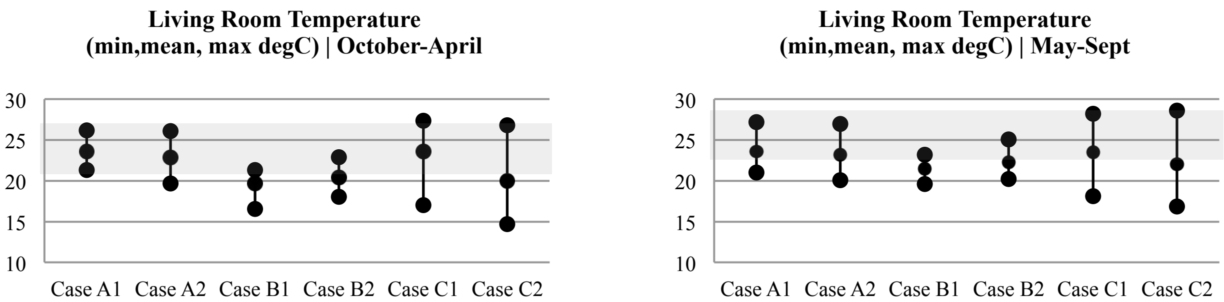


Figure 1. Minimum, mean and maximum temperatures in living rooms during the heating and non-heating periods.

eration and control of the heating and mechanical ventilation systems, with occupants in development B finding summer temperatures high, probably due to uncontrollable and excessive heating from the underfloor central heating system. Interviews with occupants revealed that control over heating is considered problematic in Developments A and B that feature air source heat pumps and underfloor heating, as these are unfamiliar technologies. The unfamiliarity is confounded by the lack of clear guidance in the Home User Guide. Occupants also appear confused about the operation of the MVHR system, which they also perceive as expensive because it is 'always on', to the extent that they manually override it and ventilate their houses by opening the windows on a daily basis to tackle poor levels of indoor air quality, despite the heating being on.

Interestingly, occupant expectations and perception of comfort has a direct impact on indoor environmental conditions. Monitored indoor temperature data was recorded in the living room (and bedroom) spaces of the case study dwellings during the monitoring period (January 2013–December 2013). Mean winter temperatures ranges between 20 and 24 ˚C across the houses, with three out of six dwellings having mean living room temperatures >22 ˚C (Figure 1). Peak winter temperatures >26 ˚C were observed in the majority of the living rooms (four out of six). Analysis showed that in most cases, winter temperatures in living rooms exceed 26 ˚C for less than 1 % of the occupied hours (daytime), but in Cases A2 and C1, this occurs 1.2 and 2.4 % respectively, indicating that these living rooms are very warm even during the heating season. Mean summer temperatures range between 21 and 24 ˚C, with four out of six houses experiencing max living room temperatures in summer above 27 ˚C. In all Cases, with the exception of Case B1, summer living room temperatures exceed 28 ˚C for more than 1 % of occupied hours. In Cases C2 and A1 in particular summer living room temperatures remain above 28 ˚C for 4 % and 4.75 % of occupied hours respectively, indicating risk of overheating.

Figure 2 shows the average hourly temperatures and RH levels recorded in the living rooms of the six case study houses during January and August. The lowest winter temperatures are recorded in Cases B1 and B2, often falling below the suggested EN15251 comfort levels of 20–26 °C (CEN, 2007). Case B1 has the lowest mean winter temperatures due to occupant's efforts to minimize their electricity bills by heating their house during the night only. On the other hand, Cases A1 and C1 have the highest winter temperatures as they keep their thermostats at around 25–27 °C throughout the day. Summer temperatures range between 21 and 26 °C in most cases, with the exception of Case C2 that presents the greatest scatter during both winter and summer, with summer temperatures often exceeding 27 °C and reaching 29 °C at times. Low winter temperatures recorded in Case C2 are due to prolonged window opening. High indoor temperatures are affecting internal relative humidity (RH) levels, which in general are quite low; less than 50 % in the heating season (October–April) and less than 60 % in the non-heating season (May-September) in most cases, as shown in Figure 2. In the non-heating season both RH levels and temperatures increase, but remain inside the CIBSE recommended comfort limits of 40–70 % (CIBSE, 2006).

Findings from occupant surveys and interviews help to contextualise the environmental conditions in the houses. In Developments A and B, temperatures during winter are generally regarded as quite comfortable, whereas summer temperatures are perceived as slightly hot. In both developments occupants complain of poor control over heating with some occupants feeling they cannot control temperatures effectively. Complaints of high summer temperatures in Developments A and B indicate that the houses are not adaptable to warm weather conditions. This might be due to the lack of shading devices, lack of cross ventilation and low thermal mass of the houses. Interestingly, in Development C both summer and winter temperatures are perceived as comfortable from the majority of the occupants despite the fact that the two case studies from Development C present the highest indoor temperatures across all six case studies. These findings indicate that the perception of comfort varies greatly between different occupants.

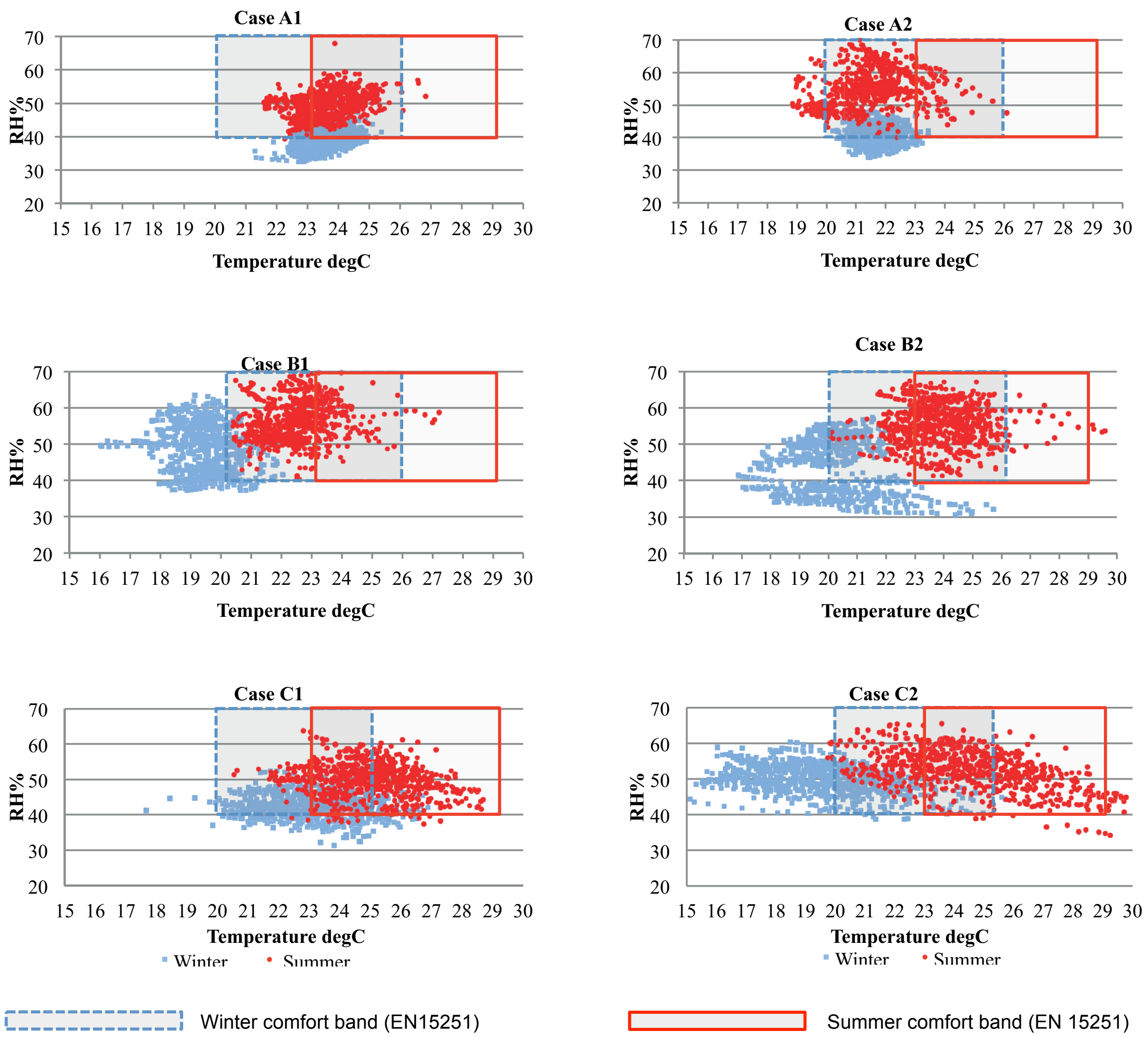


Figure 2. Average hourly temperature and relative humidity levels during winter (January) and summer (August).

The open-close state of the principal windows in living room and bedroom spaces of four case study houses (A1, A2, C1 and C2) were also monitored concurrently with environmental conditions to better understand the relationship between human interactions and the physical environment of homes. The hourly percentage of window opening in living rooms and bedrooms for the heating season is plotted against hourly average internal temperatures, as shown in Figure 3. During the heating season occupants in Cases A1 and A2 tend to keep their windows mostly closed and indoor hourly temperatures are kept steady throughout the day. On the other hand, indoor temperatures in C1 and C2 present a higher diurnal variation as occupants leave their windows open for longer periods. While in C1 occupants tend to open the living room window and backdoor when indoor temperatures rise, in Case C2 occupants leave the living room window open throughout the day. This habitual behaviour might explain the high energy usage of cases C1 and C2.

Window opening in Cases A1, A2, C1 and C2 was also correlated with CO_2 levels in the living rooms and bedrooms. Levels of CO_2 correlate well with human occupancy and human-generated pollutants and provide a useful indicator of relative levels of ventilation and indoor air quality. It is generally accepted that levels above 1,000 ppm are indicative of poor air quality and ventilation rates (Porteous, 2011), which corresponds to a ventilation rate of 8 l/s per person. Occupants in Cases C1 and C2 had manually overridden the MVHR systems (discussed in following section) and were relying on window opening to ventilate their houses. The effect of this can be seen in Figure 4. CO_2 levels during sleeping hours are much higher in C1 bedroom compared to A2 bedroom that has the same occupancy (2 adults) but is also less airtight. There appears to be a correlation between the high CO_2 levels and window opening in Case C2, as occupants tend to keep the bedroom window open during the night and also open the living room window in the afternoon, both during times when CO_2 levels are elevated.

The amount of time CO_2 levels are above the limit of 1,000 ppm during a year in each of the four case study houses is graphed in Figure 5. While in Cases A1 and A2, CO_2 levels in the living rooms range between 500–750 ppm for the majority of the time (50–60 %); CO_2 levels are lower in Cases C1 and C2 living rooms remaining <500 ppm for 50 % of the time. This is directly related to the window opening behaviour as occupants in Cases C1 and C2 habitually open their windows more frequently than occupants in Cases A1 and A2. Despite this, living room CO_2 levels in Cases A1, A2 and C1, levels exceed 1,000 ppm for 3–4 % of the time, while bedroom CO_2 levels exceed 1,000 ppm for 4–6 % of the time in Cases A1 and C2, and for 12–17 % of the time in Cases A2 and C1. High bedroom CO_2 levels in Cases A2 and C1 are partly due to room occupancy levels (2 occupants per room during the night). The differences between living room and bedroom CO_2 levels imply that ventilation rates are not adequate when occupants are asleep (and opportunities for adaptive control are limited), and particularly when the MVHR is not working properly.

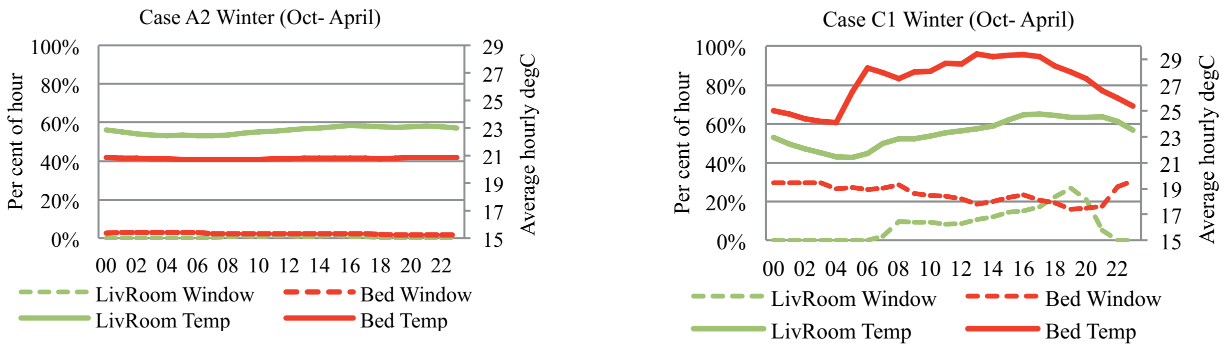


Figure 3. Hourly average temperatures and hourly percentage of window opening across a day.

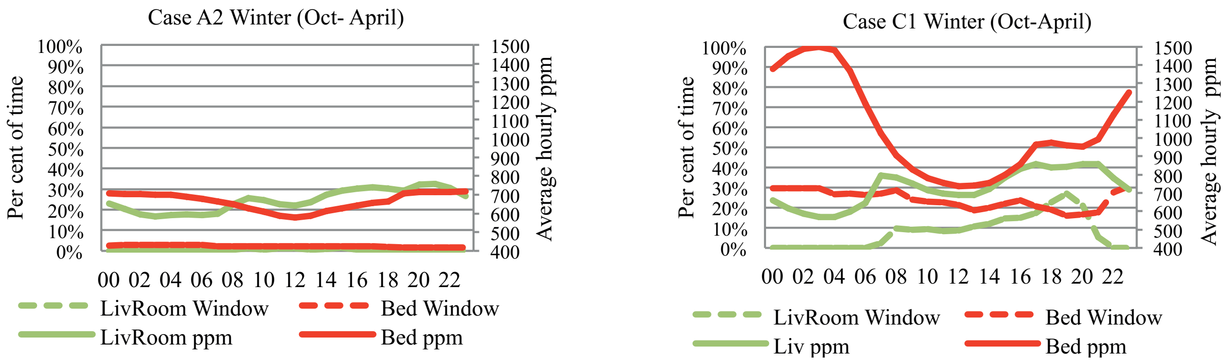


Figure 4. Hourly average CO_2 levels and hourly percentage of window opening across a day.

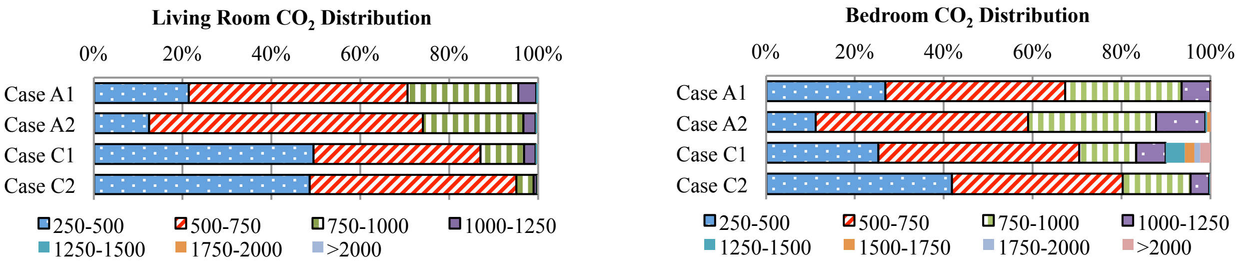


Figure 5. Distribution of CO_2 levels in living rooms and bedrooms (January–December 2013).

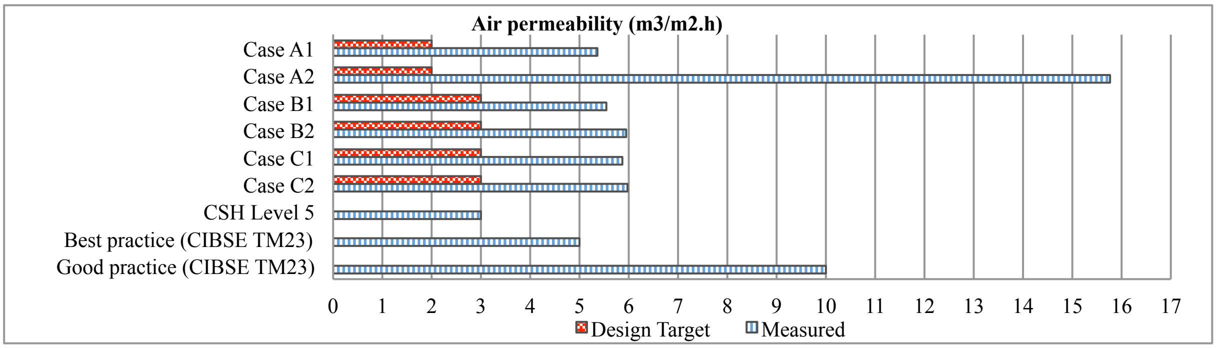


Figure 6. Comparison of measured and design air permeability.

Performance of fabric, services and systems

BUILDING FABRIC PERFORMANCE

The fabric performance of the case study dwellings was tested using diagnostic field tests[3] that included: air permeability tests, in situ U-value tests and infrared thermography. Overall wall insulation levels were found to be as-designed in all cases, even though thermographic images revealed some heat loss through window and door frames and thermal bridges across ceiling beams and thresholds. Air permeability tests, on the other hand showed that all six dwellings missed their design air permeability target of 2–3 m^3/m^{2}h with most cases being twice as high as designed (Figure 6). All case study houses failed to comply with the best practice air permeability rate (5 m^3/m^2.h) recommended by CIBSE TM23 (CIBSE, 2000). In fact, Case A2 (15 m^3/h.m^2 @ 50 Pa) did not even meet the 2010 Building Regulation standard (10 m^3/m^2.h), demonstrating inadequate enforcement of compliance and verification procedures. These values are similar to those measured after completion and before occupancy, indicating construction and workmanship issues rather than occupant intervention. In Case A1 in particular, the high air permeability rate is due to a large breach in the air-permeability membrane between the EAHP cupboard and the roof space. It is interesting to note that none of the case studies achieved actual air permeability levels of 5 m^3/m^{2}h at which MVHR systems are recommended (EST, 2010).

3. Air-permeability and U-value tests were undertaken by external contractors under the supervision of the LCB group. All tests were carried out after occupant move-in and during the monitoring period of 2013–2014.

HEATING, VENTILATION AND ELECTRICITY-GENERATING SYSTEMS

The design, installation and commissioning of heating and ventilation systems was examined to ensure the systems are capable of creating the required environmental conditions and whether the operational strategy was likely to deliver the desired performance and comfort for the occupants. Several issues were revealed in the installation and commissioning of heat pumps in developments A and B, and mechanical ventilation systems across all three developments. Table 3 summarises the common issues across the three developments.

MVHR systems were chosen in all the three developments to achieve code compliance at the design stage. The developers (housing association or the local authority) reported that they had little knowledge and experience in the design, specification, installation, commissioning and maintenance of MVHR systems. In addition, the sub-contractors failed to install and commission the MVHR systems according to the specifications, as revealed by the commissioning review undertaken during the study. Poor maintenance further aggravated the problems, as the commissioning errors were not addressed effectively. These issues led to imbalance between supply and extract air up to 53 % in Case A1 and 28 % in Case C2; frequent breakdowns (Cases B1, B2), noise (Case C1) and cold draughts (Case B1). The MVHR supply and extract terminals in all cases were not locked in fixed positions, allowing the occupants to adjust them at will, resulting in insufficient fresh air supply, adding further to system imbalance and affecting indoor air quality. System imbalances can also lead to increased heat loss and energy use, as well as increased system resistance that leads to noise (Price and Brown, 2012). Cold draughts due to system imbalance led occupants to completely switch off the MVHR system in Cases B1 and C1 and to

Table 6. Common issues highlighted by review of systems installation and commissioning.

	Development A	Development B	Development C
MVHR imbalance between supply and extract air flow	×	×	×
MVHR unit located in loft inaccessible		×	×
MVHR terminals not locked in fixed positions	×	×	×
MVHR terminals closed by occupants due to cold air		×	×
Several MVHR system breakdowns	×	×	×
Poorly commissioned heating controls	×	×	

close the supply terminals in Case C2, potentially compromising the indoor air quality.

The performance of the heating systems did not always meet the specification standards. In Cases A1 and A2 the Coefficient of Performance (COP) of the Exhaust Air Heat Pumps (EAHP, which provides space heating and hot water) installed was measured as 1.4, while the design specification average COP was 2.6. Findings from the Energy Savings Trust field trials reveal how commissioning and control issues can affect the performance of heat pumps (EST, 2013).

In addition to this, the connection of heating controls with room thermostats was also found to be problematic in most houses. In Development A, a commissioning check before the move-in revealed that zone thermostats were not properly wired to the master thermostat, an issue that was resolved as part of the BPE study. In Development B, some of the wireless room thermostats had not been connected to the heating systems resulting in the heating being constantly on, even during summer. This issue made occupants in Cases B1 and B2 feel a perceived lack of control over heating and made them sceptical towards the heat pump and other technologies used in the houses. The commissioning problem was discovered during the study several months after the move-in following occupant complaints of overheating. Due to the system underperformance and perceived lack of control, occupants in Case B1 turned off the heating system completely during the day, in an attempt to save energy, without realising the unintended consequences this would have on the energy and environmental performance of the house. In Case B2, occupants on the other hand, had not realised the system failure and experienced very high temperatures over a prolonged period of time during summer.

Actual energy use and fuel costs

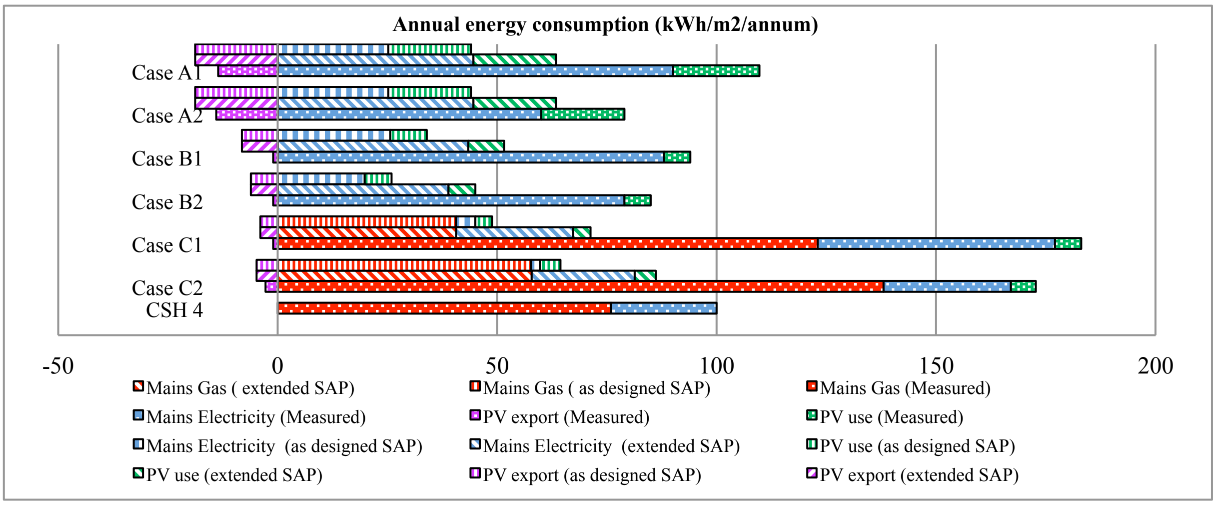
The effect of the under-performance of services and systems, inadequate occupant understanding and unintended consequences can be observed through the analysis of the monitoring data on gas and electricity, for the period between January 2013 and December 2013. Comparison of actual annual energy use with 'as designed' Standard Assessment Procedure (SAP)[4] calculations reveals that actual electricity and gas use is between 2 to 4 times higher than the SAP estimated energy use and actual CO_2 emissions are between 4 to 12 times higher than calculations. These discrepancies are partly due to the fact that SAP does not cover all end uses of energy such as electricity used for appliances. To overcome this, SAP calculations were enhanced to include electricity for lighting and appliances and energy used for cooking, using an MS Excel worksheet provided by the Technology Strategy Board as part of their national Retrofit for the Future programme. As shown in Figure 7, annual energy use exceeds the extended SAP estimates by a factor of 2 in most cases and by a factor of 3 in Case C1, with actual emissions being 2 to 3 times higher than the extended SAP emissions estimate.

The key reasons leading to this performance gap are the underperformance of the fabric and systems (poor air tightness, inadequate commissioning of the heat pumps and poorly balanced MVHR system airflow), and also the unintended consequences related to lack of control, system misuse and occupant expectations, as explained in the previous sections. In fact, occupant expectations and lack of control leads to excessive heating from the underfloor central heating system (Developments A and B) and always on radiators and winter window opening patterns (Development C), all of which contribute to the poor energy performance.

Interesting findings emerge when cases are compared against each other. Case A1, although designed for CSH Level 5, consumes more electricity than Cases B1 and B2, which were designed for CSH 4. This is partly due to the lower Coefficient of Performance (COP) of the exhaust air heat pumps (EAHPs) installed in Cases A1 and A2 measured as 1.4, compared with the COP of the ASHP in Cases B1 and B2 specified as 3.13. On the other hand, Cases C1 and C2 (with conventional gas central heating and MVHR systems) have the worst energy performance in the sample.

There is also significant variation in the energy performance of identical houses within the same development designed to the same standard and with similar occupancy patterns. For instance, occupants in Case A2, which has higher air permeability than A1, consume 30 kWh/m^2/annum less electricity than their neighbours in Case A1 (Figure 9), implying the direct effect of occupant behaviour and expectations on housing performance. Occupants in Case A2 keep their thermostat at 19 °C and are more energy conscious than their neighbours in A1 who keep the thermostat between 25–27 °C and also do not understand the operation of the heating controls. This results in higher annual energy use and associated CO_2 emissions in Case A1 by a factor of 1.4 when compared against Case A2.

4. The Standard Assessment Procedure (SAP) is the UK Government's recommended method system for measuring the energy rating of residential dwellings. It calculates the typical annual energy costs for space and water heating, and, from 2005, lighting.



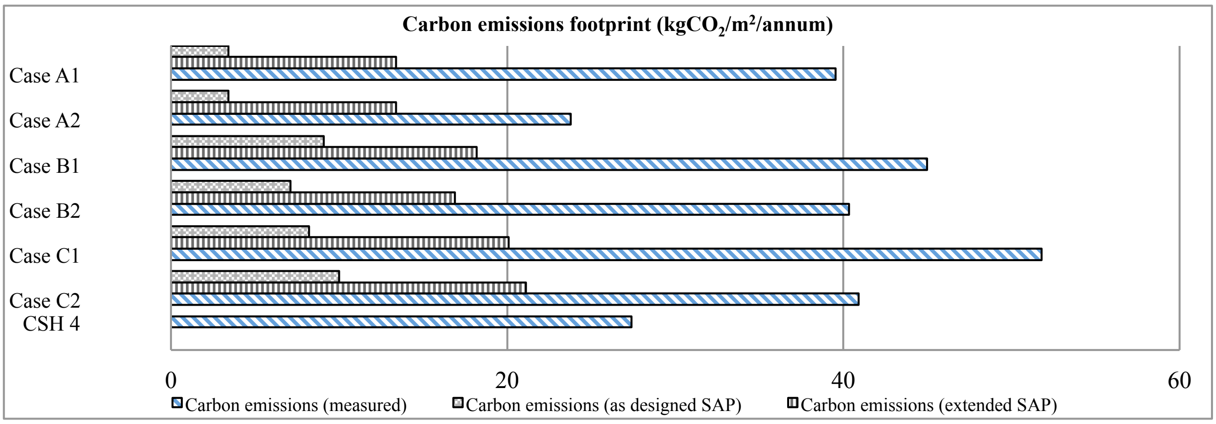


Figure 7. Comparison of actual annual energy consumption and CO_2 emissions with SAP and Extended SAP model predictions across all cases (January 2013–December 2013). CO_2 emission factors: Electricity 0.517 $kgCO_2/kWh$, Gas 0.198 $kgCO_2/kWh$. (Benchmarks and carbon factors taken from DomEARM.)

Also in Development B, annual CO_2 emissions and actual energy use in Case B1 are higher than those of Case B2 by a factor of 1.1, even though Case B2 is occupied by more adults and for longer hours. This is due to poor occupant understanding of the ASHP and underfloor heating. Although occupants of cases C1 and C2 prefer to set their thermostats as high as 30 °C throughout the day, the annual gas use of Case C2 only slightly exceeds that of Case C1, since Case C2 occupants also habitually leave the living room windows open throughout the day even during winter. However electricity use in Case C1 is higher than that of Case C2 due to the occupants' washing and showering regime. Energy by end-uses is shown in Figure 8. The unregulated loads, including small power, cooking, refrigeration and wet appliances, account for 32 % of total energy use in Case A1, 35 % in Case A2, 28 % in Case C1 and 14 % in Case C2, indicating the underestimation of the domestic energy demand through SP type models is one of the parameters leading to the performance gap. The discrepancies in energy use between case study houses indicate the effect of individual occupant behaviour and control.

Because of all the aforementioned issues, actual fuel bills across all case study houses are very high, despite the developments being designed to reduce energy use and fuel bills. As shown in Figure 9, fuel bills of five out of the six case studies are even higher than a typical household in UK (Ofgem 2013), and interestingly, much above the SAP estimated cost (between 4 and 12 times) questioning the use of compliance tools (such as SAP) for decision-making by housing associations. It should be noted that estimated annual costs rise significantly when taking into account the energy use of appliances, as done in the extended SAP calculation.

Interestingly occupants also attribute their high electricity bills to frequent breakdowns of the MVHR systems (all three developments), poor performance of the heat pumps and always-on under-floor central heating system (Developments A and B). This is why in case B1 occupants turned off the MVHR system and underfloor heating to save on the fuel costs, without realising the unintended consequences on indoor environmental conditions and health. Such inadvertent actions by inhabitants could become commonplace if the fabric and system performance of low energy homes is not improved.

Conclusions

With requirements for as-built performance are likely to be included in future Building Regulations, the importance of achieving real performance that matches predictions, is becoming a mainstream issue (ZCH, 2013). There is clear evi-

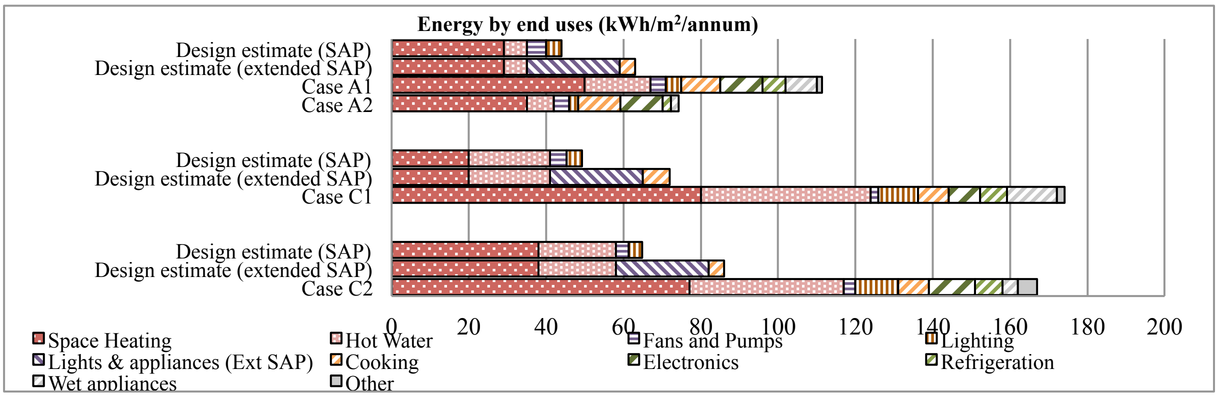


Figure 8. Energy by end uses (January 2013–December 2013).

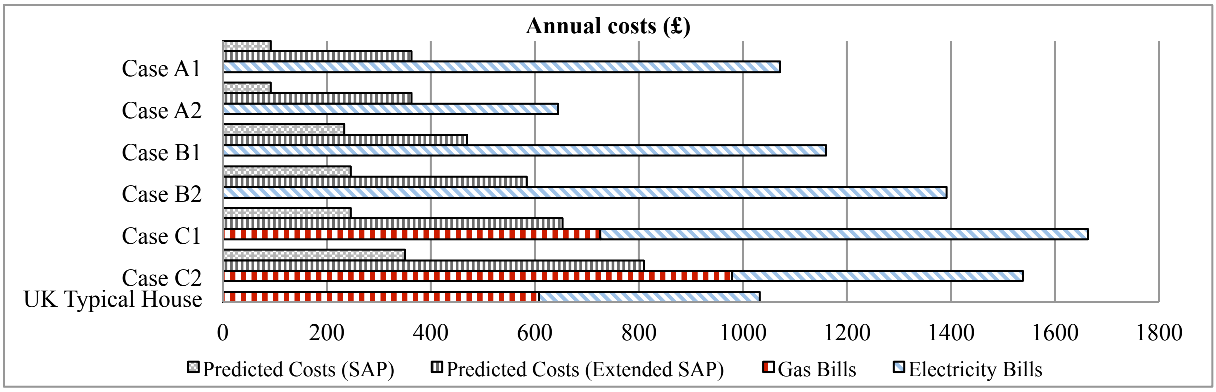


Figure 9. Annual energy costs (January 2013–December 2013). Typical UK domestic energy bills are based on average household bills (Ofgem, 2013). (For SAP, extended SAP and actual energy use, PV export compensation was taken into account. However, it should be noted that social housing tenants do not receive any feed-back tariffs that goes directly to the building owner.)

dence that actual energy use and environmental performance of low/zero carbon housing is affected by the interdependencies between physical performance of the fabric, services and systems as well as the occupants' understanding of the systems, expectations and perception of comfort and their habitual behaviours. Issues such as higher than predicted heat losses, that occur through higher than expected air permeability levels and un-balanced MVHR systems, combined with poor commissioning of systems and underperformance of the low-carbon technologies (MVHR and heat pumps), limited control and lack of knowledge on the daily and seasonal operation of systems due to poor or confusing guidance, as well as occupant behaviour and habits, resulted in poor use of systems and increased energy use. Conflicting, confusing and non-intuitive heating controls has led to poor occupant control over heating. Such unusable systems and strategies make occupants sceptical towards them and can elicit different reactions from different occupants who may often look for ways to override the systems at the expense of energy use and environmental conditions. However, the reality is that most occupants are doing the best they can with limited knowledge of uncoordinated and inefficient systems. For houses to perform as intended it is important to tackle these issues right from the design stage through to specification, construction, handover and operation.

There is a need for integrating the heating and ventilation systems and controls strategy early in the design process, to provide a simpler approach that occupants can understand and operate more easily (BSRIA, 2014). There is an urgent need for a more considered, robust and effective design of ventilation strategies that are integrated with the heating systems that have closer control of heat delivery. Seasonal commissioning (at least in summer and winter) of services and systems should be undertaken for new low energy houses especially with mechanical ventilation systems and technologies such as heat pumps. Control interfaces need to be intuitive, clearly labelled and properly designed, and installed in an accessible location. Occupants need to be trained through graduated and extended handover that involves occupants trying out systems and controls in the presence of trained housing officers, supplemented by visual home user guides offering clear guidance on the daily and seasonal operation of systems and controls. This also highlights the need for re-defining the role of housing or tenant liaison officers (of Housing Associations) in engaging with social housing tenants to manage their expectations and also retraining them for summer and winter operations of their low energy homes. Further research is required to understand the impact of such deeper engagement on occupant understanding and operation of services and systems. Findings also point to the need for having an open discussion amongst industry, Government and academia in order to understand deeper, the balance between ventilation and airtightness levels in low/zero carbon homes for achieving good levels of indoor air quality.

Wider lessons learnt from the study for policy makers, industry and academia are as follows:

- As highlighted by the review of fabric performance, robust detailing of joints, junctions and thresholds should be carefully followed during design and construction stages. Weaknesses in thermal performance of building fabric can be picked up using a combination of diagnostic techniques especially for early detection of problems.
- Accurate 'as-built' energy models should become mandatory and be enforced rigorously for all projects of all scales to record design and procurement changes that affect energy performance. This would involve updating SAP models using 'as-built' data to gain a better understanding of the expected performance of the building.
- Proper documentation of housing performance should be enforced. Commissioning records of services and systems should be used to check the performance of heating and ventilation systems through seasonal commissioning.
- Good sub-metering data can provide deep insights for residents and developers, as to how and why energy is used and wasted. Arrangements for sub-metering domestic energy use should be carefully considered during the design stage.

The study has not only highlighted issues of underperformance of fabric, services and systems in low carbon housing, but also shown how BPE-based approach can help to discover and fix faults that would otherwise go unnoticed and become serious issues. Without this level and depth of evaluation, the gap between designed and actual energy use could widen and Government national CO_2 targets could be compromised.

References

Behar, C., Chiu L.F., 2013. Ventilation in energy efficient UK homes: A user experience of innovative technologies. eceee 2013 Summer Study Conference Proc.

Boardman, B., 2007. Home Truths: A low-carbon strategy to reduce UK housing emissions by 80 % by 2050. http://www.foe.co.uk/sites/default/files/downloads/home_truths.pdf

Bordass, B., Leaman, A., Bunn, R., 2007. Controls for End Users: A guide for good design and implementations, Building Controls Industry Association (BCIA), www.bsria.co.uk.

BSRIA, 2014. The Soft Landings Framework for better briefing, design, handover and building performance in-use. Retrieved from https://www.bsria.co.uk.

CEN Standard EN15251, 2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics Bruxelles: European committee for Standardisation.

Chartered Institution of Building Services Engineers (CIBSE), 2006. Guide A: Environmental design. London, CIBSE.

CIBSE, 2000. TM 23, Testing Buildings for Air Leakage. CIBSE, London.

Davies, M., Oreszczyn, T., 2012. The unintended consequences of decarbonising the built environment: A UK case study, Energy and Buildings, Volume 46, March 2012, Pages 80–85.

Department for Communities and Local Government (DCLG), 2009. Definition of Zero Carbon Homes: Impact Assessment www.communities.gov.uk/publications/planningandbuilding/impactzerocarbon.

Energy Saving Trust (EST), 2013. Detailed analysis from the second phase of the Energy Saving Trust's heat pump field trial. https://www.gov.uk

Energy Savings Trust (EST), 2010. Ventilation and Airtightness in New Homes. www.energysavingtrust.org.uk

European Union (EU), 2010. Directive 2010/31/EU of the European Parliament and of the council of 19 May 2010 on the energy performance of buildings 2010 http://ec.europa.eu/energy/efficiency/buildings/buildings_en.html.

Firth, S., Lomas, K., Wright, A., Wall, R. 2008. Identifying trends in the use of domestic appliances from household electricity consumption measurements. Energy and Buildings, 40, 926–936. doi: 10.1016/j.enbuild.2007.07.005.

Gill, Z.M., Tierney, M.J., Pegg I.M., and N. Allan, N. 2010. Low energy dwellings: the contribution of behaviours to actual performance. Building Research and Information, 38:5, 491–508.

Gupta R., Gregg, M., Cherian,R., 2013. Tackling the performance gap between design intent and actual outcomes of new low/zero carbon housing, eceee 2013 Summer Study proceedings, France, 1–6 June 2013.

Gupta, R., Kapsali, M., 2014. How effective are 'close to zero' carbon new dwellings in reducing actual energy demand: Insights from UK. PLEA Conference Proc., Ahmedabad, India.

Monahan, S. & Gemmell, A., 2011. How occupants behave and interact with their homes: The impact on energy use, comfort, control and satisfaction, Milton Keynes: NHBC Foundation.

Ofgem, 2013. Review of typical domestic consumption values. https://www.ofgem.gov.uk/ofgem-publications/74735/tdcv-review-consultation.pdf

Porteous, C., 2011. Sensing a historic low-CO_2 future. In: Mazzeo (Ed.) Chemistry, emission control, radioactive pollution and indoor air quality. Croatia: Intech. Retrieved from http://www.intechopen.com.

Preiser, W., Vischer, J. (2005) Assessing Building Performance, Elsevier, Butterworth, Heinemann.

Price S., Brown H., 2012. Mechanical Ventilation with Heat Recovery: Designing and implementing a robust and effective ventilation system. http://www.encraft.co.uk

Sharpe, T., Shearer, D., 2013. "Scenario testing of the energy and environmental performance of the Glasgow House." PLEA 29th Conference, Munich, Germany, September 10–12.

Steemers, K. and G.Y Yun. 2009. Household energy consumption: a study of the role of occupants. Building Research and Information, 37 (5–6), 625–637.

Stevenson, F., Rijal, H.B., 2010. Developing occupancy feedback from a prototype to improve housing production, Building Research & Information, 38: 5, doi: 549–563, 10.1080/09613218.2010.497282.

Thompson, P., Bootland, J., 2011. "GHA monitoring programme 2009–11: Technical report. Results from Phase 1: Post-construction testing of a sample of highly sustainable new homes". Good Homes Alliance. http://www.goodhomes.org.uk/downloads

Topouzi, M., 2013. Low-carbon refurbishments: How passive or active are technologies, users and their interaction?, eceee 2013 Summer Study proceedings, France, 1–6 June 2013.

TSB (Technology Strategy Board), 2012. Competition: Building Performance Evaluation webpage, http://www.innovateuk.org.

UKGBC (United Kingdom Green Building Council), 2008. The definition of zero carbon, Zero Carbon Task Group report.

Wingfield, J., Bell, M., Miles-Shenton, D., Seavers, J., 2011. Elm Tree Mews Field Trial. CeBE Report http://www.leedsmet.ac.uk/as/cebe/projects/elmtree.

Zero Carbon Hub, 2013. Closing the gap between designed and as-built performance. http://www.zerocarbonhub.org

Acknowledgements

We are grateful to UK Government's Technology Strategy Board's (now innovate UK) Building Performance Evaluation programme for funding this research project. Our sincere thanks to the occupants, clients and project design teams for their help and support during the study.