Evaluating the influence of building fabric, services and occupant related factors on the actual performance of low energy social housing dwellings in UK

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Abstract

This paper empirically investigates the influence of building fabric, services and occupant related factors on actual energy use of six case study dwellings, located in three new low energy social housing developments in UK, covering a variety of built forms and construction systems (timber frame, hempcrete, steel-frame). Physical monitoring of indoor environment and window-opening is cross-related with building fabric and systems' performance, and qualitative data gathered through occupant surveys, review of control interfaces and handover guidance, to understand the causes of the gap between modelled and measured energy use. Actual energy use is found to exceed design expectations by a factor of three, questioning the need for whole-house mechanical ventilation heat recovery (MVHR) systems at measured air permeability rates of $6m^3/(h.m^2)$ against the design target of $3m^3/(h.m^2)$. Lack of proper commissioning of MVHR and heating systems, combined with inadequate user comprehension about their operation and control leads to occupant 'misuse' wherein systems are de-activated, thereby negatively affecting indoor air quality. This is confounded by occupant factors related to higher demand temperatures, unexpected opening of windows during winters due to under-performance of MVHR combined with habitual behaviours, and over-use of heating systems to compensate for higher than expected air permeability.

Key words: social housing; energy; environment; building performance evaluation; occupant behaviour

Introduction

In the UK, as with other European countries, about 27% of all carbon dioxide (CO_2) emissions are related to energy use in housing (DCLG, 2009; EU, 2011; HMG, 2008). 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.

Despite this, 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 up to 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, Huebner et al., 2015; Jones and Lomas 2015; Gram-Hanssen,

2010), 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, Ridley et al., 2014).

Furthermore, new housing in the UK is experiencing rapidly changing standards, especially in the social housing sector (which represented 25% of all new homes in 2013/14 (DCLG, 2014)). Consequently, innovations have been made in materials, technologies and construction (Sharpe and Shearer, 2013). Given the risk of high energy costs associated with potential underperformance of such experiments and innovations, it could be argued that performance of social housing dwelling needs to be systematically evaluated in order to learn lessons and make the required changes to improve future designs. 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; Huebner et al., 2015).

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). In order to effectively map and address these issues, new approaches are needed that are able to capture the complexity of the built environment. Building Performance Evaluation (BPE) is widely acknowledged as an important mixed-method approach for gaining a deeper understanding of the environmental and energy performance of buildings. Despite this recognition, limited studies have been undertaken in the social 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.

Social housing is a means of providing accomodation that is affordable to people on low incomes. As such, residents are often more vulnerable both financially and physically. Therefore the promise of low energy bills in addition to lower than market-rate rent is very appealing. Since providers of social housing are responsible not only for the long term management and maintenance of the property, but also for their building's residents, it is important that they understand the risks involved in failing to deliver on the designed performance targets of a new dwelling (NEF, 2015): Occupants may be more at risk of illness due to indoor envrionmental conditions, and of fuel poverty - being faced with fuel bills that are unaffordable and unexpected given the 'low energy housing' status of their dwelling.

This study aims to considers all aspects of housing performance – building fabric, services and occupant related factors to systematically assess the reasons for the gap between modelled and measured energy use (and fuel costs) in social housing dwellings. Specifically the study investigates the actual energy use and environmental conditions of six case study

social housing dwellings, located in three new low energy social housing developments in the UK, using the mixed-methods empirical approach of Building performance evaluation (BPE). Quantitative data on the performance of building fabric, services and indoor environment, are cross-related with qualitative data on communication of design intent, usability of control interfaces and occupant behaviour, to understand the reasons for the gap between modelled and actual energy use. Wider lessons and recommendations are drawn for the industry to reduce the gap between expected and actual performance of social housing dwellings.

Evidence of housing performance evaluation

Much of the research into the aforementioned performance gap has focussed on the building fabric performance. Indeed, evidence suggests that in a new-build dwelling, about 20-30% of the total heat loss arises from thermal bridging (Zero Carbon Hub, 2016) and up to 50% from air leakage (Energy Saving Trust, 2009). The majority of international studies (outlined in Table 1) found that test dwellings were falling short of their design targets in terms of airtightness and, consequently, with regards to energy performance.

Table 1 International studies and building fabric performance findings

Study	No. of dwellings	Building Fabric Performance
Residential air-tightness measurements, Greece (A. Sfakianaki et al., 2008)	20	Air changes/hour varied from 0.6 to 7.0 ACH (at 50 Pa). Linear relationships between total length of window frame and air tightness.
Contribution of windows and shutters on space heating in Portugal (Almeida et.al., 2017)	23	Windows contributed by 15% and roller shutters by by 44% to the rooms' permeability.
Dwelling airtightness evaluation in Ireland (Sinnott, 2016)	9	Semi-detached social houses had measured and modelled airtightness differing by up to 89%.
Air tightness in new lightweight houses in Estonia (Kalamees, 2007)	32	Field measurements found a mean air leakage rate of 4.2 $m^3/h/m^2$@50 Pa, highlighting the quality of workmanship as key to airtightness.
Airtightness of residential buildings in Finland (Vinha et al., 2015)	226	Workmanship identified as a key contributor to airtightness
Relationships between building characteristics and airtightness of Dutch dwellings (Bramiana et al., 2016)	Data gathered from several organisations	Air leakage paths identified included junctions and joints, openings, service penetrations and fittings
Building leakage, infiltration, and energy performance analyses for Finnish detached houses (Jokisalo et al., 2009)	170	An almost linear relationship between average infiltration rate and heating energy use with the building leakage rate. 15–30% of the space heating energy associated with infiltration.
Air-tightness and its Influencing factors on airtightness inpost-2006 new-build dwellings (UK) (Pan, 2010)	287	Critical influencing factors for airtightness include management, build method and dwelling type. Dwelling type and build method had a two-way interaction, indicating an interactive rather than synchronous relationship. Precast concrete builds were significantly more airtight than masonry and reinforced concrete builds.

A sample of BPE studies in the UK are shown in Table 2, measuring the building fabric and energy performance of dwellings covering both social housing and private dwellings. The meta-analysis of BPE data of 83 social housing dwellings by NEF (2015) revealed that air tightness of 46% of the BPE test dwellings was below the design intent. Of the 14 dwellings in the AIMC4 programme, five used more (up to 196% more) energy than the regulated energy usage shown in Standard Assessment Procedure (SAP) i (Gaze, 2014b). The large-scale study at Stamford Brook found the effective U-values to be double the designed values for external walls of retrofitted dwellings and nearly three times greater for floors and ceilings (Wingfield et al., 2008). Passivhaus dwellings are not exempt from these deviations from design targets. However, the gap is much lower and often negligible, with discrepancies of the order of 0.01–0.06 W/m^2K (Good Homes Alliance, 2014; Johnston et al., 2016; Guerra-Santin et al., 2013). A few studies have also shown that discrepancies that arise during the building process (design, modelling, buildability, materials, build quality, systems integration), as well as commissioning, handover and operation, can contribute to the performance gap in new dwellings (Gaze, 2014a; Wingfield, et al., 2011; Wingfield, et al., 2008).

Table 2 Domestic BPE studies and energy performance findings

BPE programme	Number of test dwellings	Building fabric/energy Performance
National Energy Foundation insights from social housing projects (Seguro 2015)	83	Air tightness of 46% of the test dwellings was below the design intent. As-built external wall U-value of 0.220 Wm^2K exceeded the average design U-value of 0.164 Wm^2K, with 9 properties failing to meet Building Regulations.
Innovate UK BPE (Palmer, et al., 2016)	350 (44 studies)	Emissions 2-3 times higher than design estimates.
AIMC4 (Gaze, 2014b)	17 (14 studied)	6 dwellings lower than estimated SAP; eight higher actual energy consumption than estimated SAP
Stamford Brook (Partners in Innovation) (Wingfield et al., 2008)	~700	Modelled lower than actual performance
Elm Tree Mews (Wingfield, et al., 2011)	4 houses & 2 flats	Modelled heating input ~2500kWh lower than actual
Good Homes Alliance Monitoring Programme (Medina et al., 2014)	4	At One Brighton, while the monitored flat did not achieve the electricity target set, over the entire development, average electricity consumption did better the design target of 45 kWh/m^2/annum. The heat demand target was also achieved in the flat and across the site.
Low Energy Buildings Database (lowenergybuildings.org.uk/)	89 new build domestic	Only estimated & measured data available for three dwellings; all below estimated target.

* 18 dwellings at St Nicholas Court (Partners in Innovation) also evaluated; however, measured in-use energy consumption is not available (R Lowe, Bell, & Roberts, 2003).

A comprehensive review of the evidence of the gap between designed and as-built energy performance of new homes (excluding occupant related factors) was conducted by the Zero Carbon Hub (2014). Fifteen issues were identified as *priority for action* and generally related to construction and commissioning phases. Seventeen further issues were identified as *priority for research* and generally related to the detailed design and verification and testing stages. Three themes were also identified as significant barriers to improving the performance gap: knowledge and skills, responsibility, and communication. These themes hint at the role of the occupant in contributing to the energy performance gap.

As evident from the review of literature, the majority of empirical studies investigating performance gap in new housing have tended to focus mainly on as-built performance by assessing issues with design, building fabric or services. There appears to be paucity of empirical studies that have systematically measured occupant understanding of the dwelling, their comfort and behaviour, which can sometimes have a positive (e.g. wearing warmer clothes to offset the need for heating) or negative (leaving windows open when the heating is on) influence on energy performance.

Methodology

Building performance evaluation (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). This paper presents data and findings from three BPE (one Phase I and two Phase II projects) studies undertaken by the authors. These studies are part of the UK Government's (Innovate UK, formerly Technology Strategy Board) £8 million 4-year national research programme on BPE (TSB, 2012) to evaluate and assess the post-construction and in-use performance of both domestic and non-domestic buildings. The programme mandated a prescribed protocol for evaluation and reporting, to maintain consistency and comparability in benchmarking and analysis. Studies include Phase I projects, which undertook post-construction testing and early occupancy, and Phase II studies, which additionally undertook monitoring of energy and environmental conditions for a 24-month period.

In this study, the actual energy and environmental performance of six low energy case study social housing dwellings were assessed through concurrent 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. These data were collected between January 2013 and December 2013 (12 months) at five minute intervals using Radiotech remote monitoring sensors and transmitted wirelessly from a RT:Wi5 data-hub. This physical data were 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. This included occupants' feedback on their washing and showering regimes and thermostat settings. Building fabric performance was tested using diagnostic field tests (air-permeability tests[ii], in-situ thermal transmittance (U-value) tests[iii], and infrared thermography[iv]) along with a review of the installation and commissioning of services and systems. The communication of design intent to residents was evaluated by observing the handover process and assessing the home user guides. Usability was 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 94m^2 and the largest being 146m^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 period of two years and Cases B1 and B2 were monitored for a period of one year. Table 3 presents an overview of the design specifications and construction details of the case studies, while Table 4 shows their occupancy characteristics.

Table 3 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^{2}K	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	4kWpk Photovoltaics	1.5kWpk Photovoltaics	1.65kWp & 1.88kWp Photovoltaics

The Code for Sustainable Homes (CSH)[iii] target ratings are given on a scale of 1 to 6, where 6 represents the highest standard. Development A was designed for CSH Level 5 (equivalent to a 100% improvement in CO_2 Dwelling Emission Rate over Target Emission Rate) and Developments B and C were designed for CSH Level 4 (equivalent to at least a 25% improvement in CO_2 Dwelling Emission Rate over Target Emission Rate). 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 2-3m^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 4). 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.

Table 1 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: 24h Weekend: 24h		Weekdays: 15:00-8:00 Weekend: 24h	Weekdays: 24h Weekend: 24h	Weekdays: 13:00-8:00 Weekend: 24h	
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

Results

Building fabric performance

With over 60% of domestic energy use coming from space heating (Department of Energy and Climate Change, 2013), the quality of the building fabric has a major effect on dwelling energy use. The building fabric performance of the case study dwellings was tested using diagnostic field tests that included: air permeability tests, in-situ thermal transmittance (U-value) tests and infrared thermography. All tests were carried out after occupant move-in and during the monitoring period of 2013-2014.

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. However, air permeability tests showed that all six dwellings missed their design air permeability target of 2-3 m^3/m^2h with most cases being twice as high as designed (Figure 1). 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 5m³/m²h at which MVHR systems are recommended (EST, 2010).
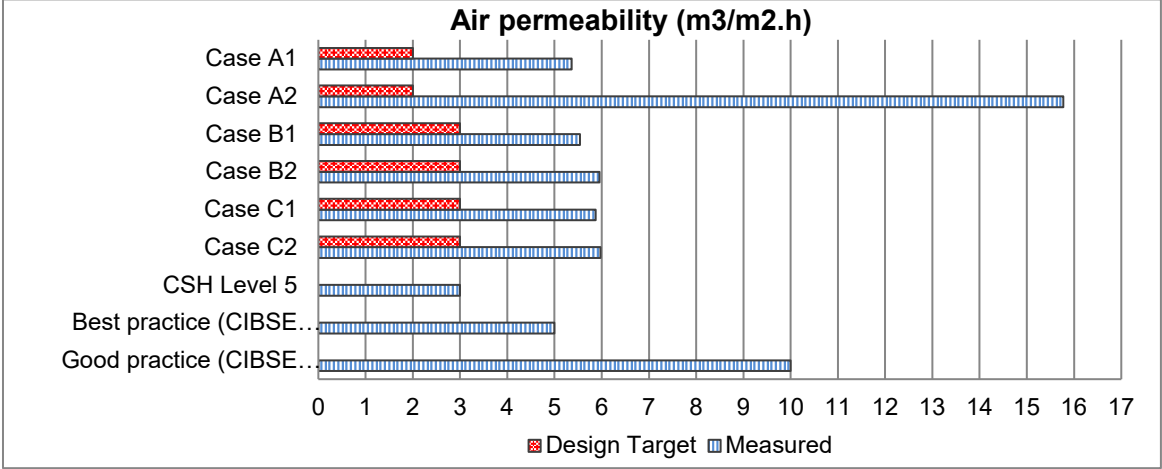

Figure 1 Comparison of measured and design air permeability.

Heating and ventilation 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 5 summarises the common issues across the three developments.

Table 5 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	✗	✗	

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 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 contrast, Case B2's occupants had not realised the system failure and experienced very high temperatures over a prolonged period of time during summer.

Occupant related factors

Occupant understanding: communication of design intent

In order to identify the influence 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 confusing. 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 6, below, summarises the common issues that were highlighted by the handover observation and review of guidance offered to the occupants. Most of these issues were prevalent across the three developments.

Table 6 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	✗	✗	✗

Since the housing associations (as social landlords) have experience of managing a large stock of tenanted properties, they were 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, and 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 were usually lengthy documents containing extensive technical details from manufacturers' manuals which were often poorly illustrated, and failed 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 was partly the reason why occupants across all the three developments seemed 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 seemed to have forgotten the information that was provided to them initially (Gupta and Kapsali, 2014). Findings also suggest that not all occupants understood 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 were 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, 2013). Table 7 below summarises the overall key issues that emerged 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, 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 understanding 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.

Table 7 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		✗	✗

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 were 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 were 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).

Occupant perceptions and experiences

To gain deeper insights into how occupant behaviour influenced housing performance, direct verbal feedback was gathered on the perceptions and experiences of the occupants once they had lived in their homes for a while and had become familiar with them. This was 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 Studies (BUS[1]) 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 8 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 were consistent with the findings from the physical performance of the services and systems, as well as the review of handover and control interfaces.

Table 8 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	✕	✕	✕

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

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1 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.

operation 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 was considered problematic in Developments A and B that feature air source heat pumps and underfloor heating, as these were unfamiliar technologies. The unfamiliarity was confounded by the lack of clear guidance in the Home User Guide. Occupants also appeared confused about the operation of the MVHR system, which they also perceived as expensive because it was 'always on', to the extent that they manually overrode it and ventilated their houses by opening the windows on a daily basis to tackle poor levels of indoor air quality, despite the heating being on.

Energy use and fuel costs

The effect of the performance of building fabric, services and systems, and occupant related factors was observed through the analysis of the monitoring data on gas and electricity use, for the period between January 2013 and December 2013. Comparison of actual annual energy use with 'as designed' Standard Assessment Procedure (SAP) calculations revealed that actual electricity and gas use was between 2 to 4 times higher than the SAP estimated energy use and actual CO_2 emissions were between 4 to 12 times higher than calculations. These discrepancies were partly due to the fact that SAP did 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 2, annual energy use exceeded 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 were 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 led 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 contributed to the poor energy performance.
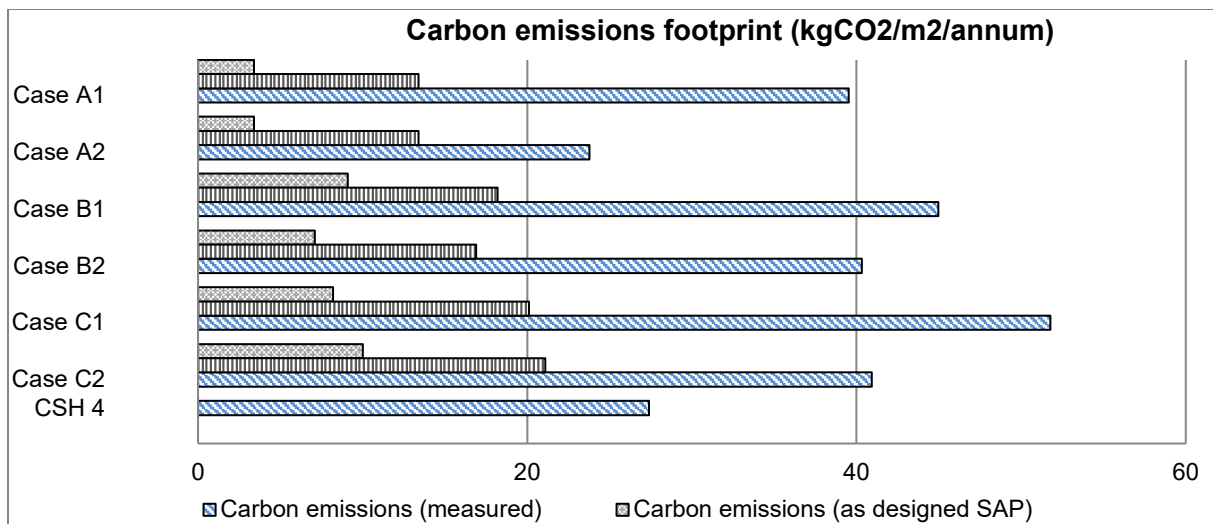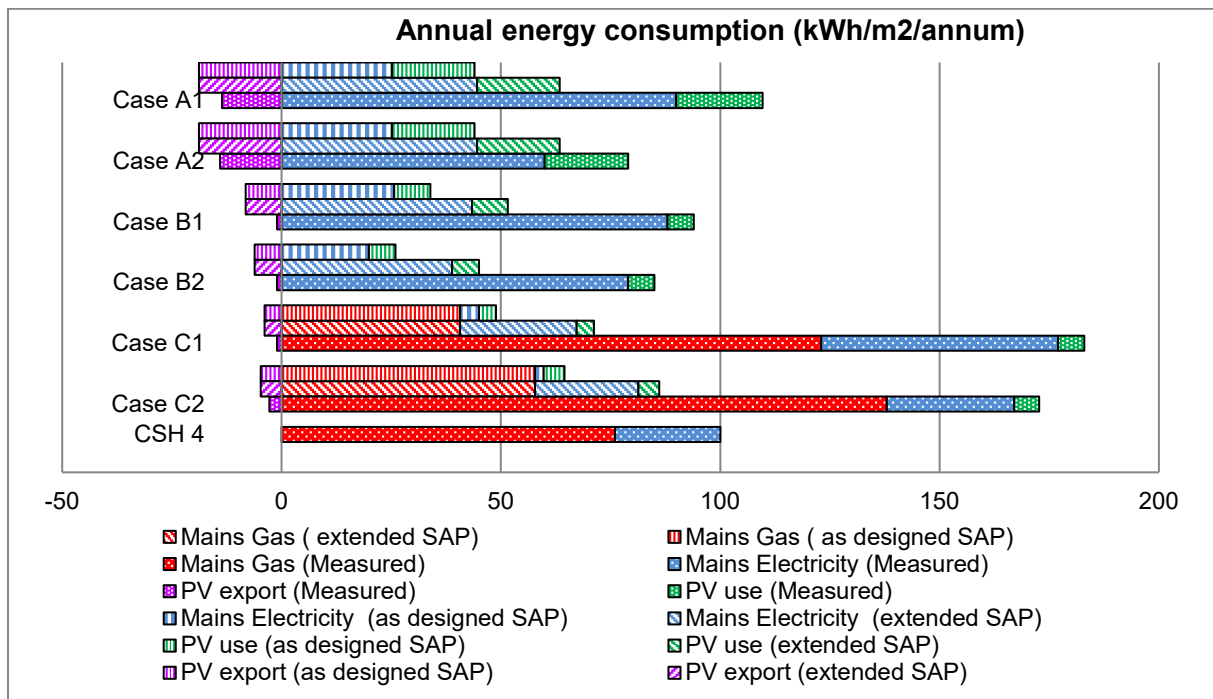
Figure 2 Comparison of actual annual energy consumption and CO_2 emissions with SAP and Extended SAP model predictions across all cases (January 2013-December 2013). CO_2 emission factors: Electricity 0.517 $kgCO_2/kWh$, Gas 0.198 $kgCO_2/kWh$.

Interesting findings emerged when cases were compared against each other. Case A1, although designed for CSH Level 5, consumed more electricity than Cases B1 and B2, which were designed for CSH 4. This was 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. However, Cases C1 and C2 (with conventional gas central heating and MVHR systems) had the worst energy performance in the sample.

There was 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 had higher air permeability than A1, consumed 30 kWh/m^2/annum less electricity than their neighbours in Case A1 (Figure 12), implying the direct effect of occupant behaviour and expectations on housing performance. Occupant feedback through surveys, in addition to on-site inspections, revealed that occupants in Case A2 kept their thermostat at 19 ^{o}C and were more energy conscious than their neighbours in A1 who kept the thermostat between 25-27 ^{o}C and also did not understand the operation of the heating controls. This resulted in higher annual energy use and associated CO_2 emissions in Case A1 by a factor of 1.4 when compared against Case A2. Also in Development B, annual CO_2 emissions and actual energy use in Case B1 were higher than those of Case B2 by a factor of 1.1, even though Case B2 was occupied by more adults and for longer hours. This was due to poor occupant understanding of the ASHP and underfloor heating. Although occupants of cases C1 and C2 preferred to set their thermostats as high as 30 ^{o}C throughout the day, the annual gas use of Case C2 only slightly exceeded that of Case C1, since Case C2 occupants also habitually left the living room windows open throughout the day even during winter. However electricity use in Case C1 was higher than that of Case C2 due to the occupants' washing and showering regime, which was identified from the occupant's daily occupancy and activity logging sheets). Energy by end-uses is shown in Figure 3. 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 was one of the parameters leading to the performance gap. The discrepancies in energy use between case study houses indicated the effect of individual occupant behaviour and control.
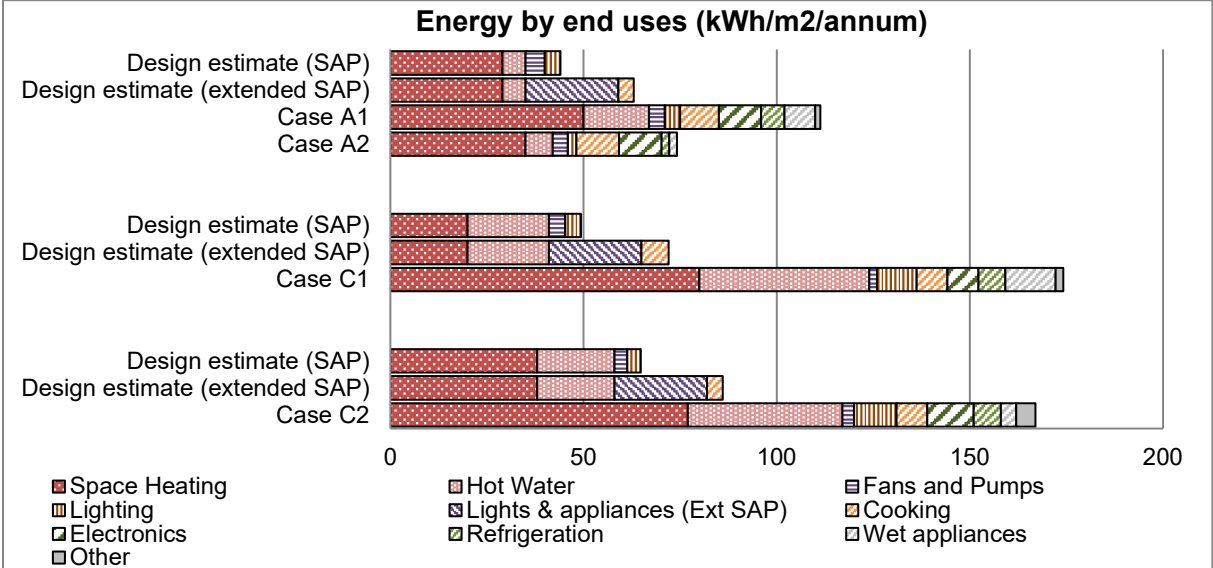

Figure 3 Energy by end uses (January 2013-December 2013).

Due to all the aforementioned issues, actual fuel bills across all case study houses were very high, despite the developments being designed to reduce energy use and fuel bills. As shown in Figure 4, fuel bills of five out of the six case studies were 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 rose significantly when taking into account the energy use of appliances, as done in the extended SAP calculation.
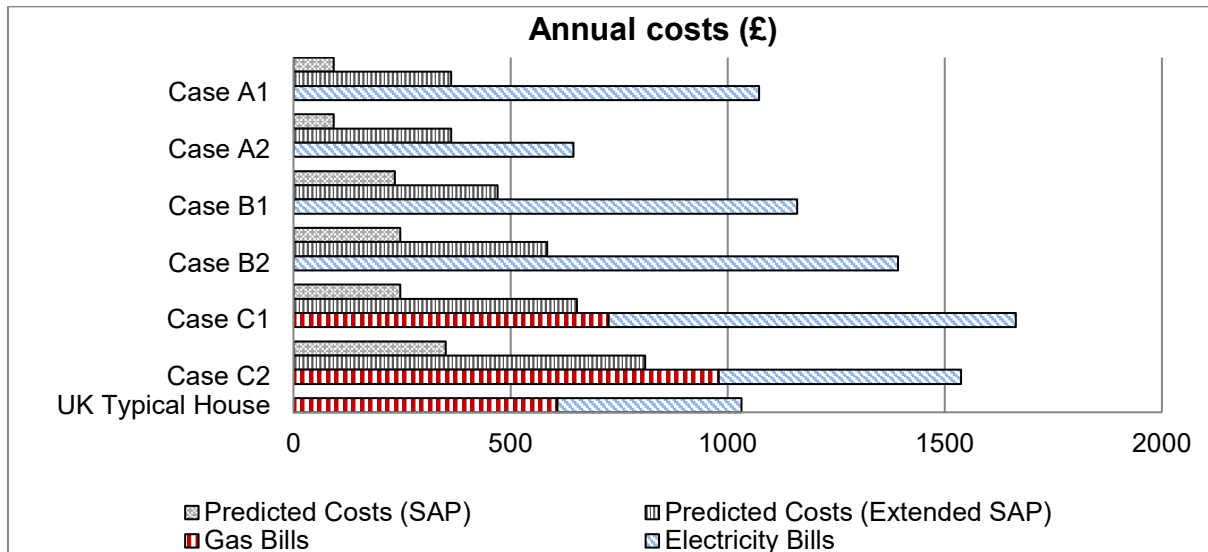

Figure 4 Annual energy costs (January 2013-December 2013). Typical UK domestic energy bills were based on average household bills (Ofgem, 2013). (For SAP, extended SAP and actual energy use, PV export compensation was taken into account. However, it should be noted that social housing tenants did not receive any feed-back tariffs that go directly to the social housing provider)

Interestingly occupants also attributed 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 was 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 residents could become commonplace if the fabric and system performance of low energy homes is not improved.

Indoor environment
Occupant expectations and perception of comfort had a direct impact on indoor environmental conditions. Indoor temperature 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 ranged between 20-24 °C across the houses, with three out of six dwellings having mean living room temperatures >22 °C (Figure 5). 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 occurred 1.2 and 2.4% respectively, indicating that these living rooms are very warm even during the heating season (Figure 6). Mean summer temperatures ranged between 21-24 °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

remained above 28 °C for 4% and 4.75% of occupied hours respectively, indicating risk of overheating (Figure 7).
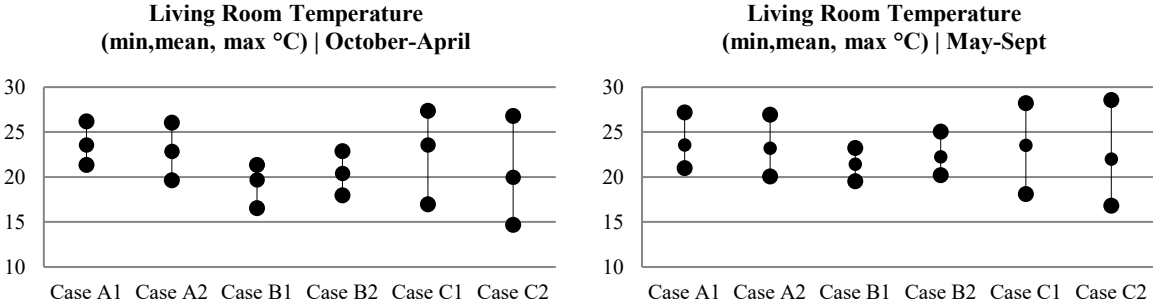

Figure 5 Minimum, mean and maximum temperatures in living rooms during the heating and non-heating periods.
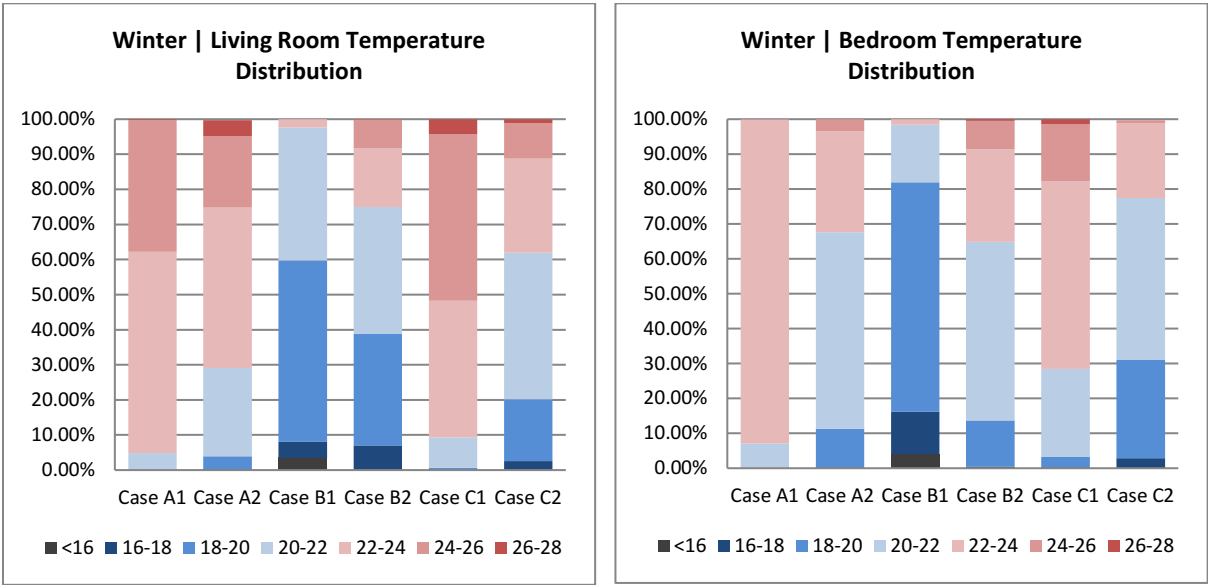

Figure 6 Temperature distributions in living rooms and bedrooms during the heating period (January-April 2013 and October -December 2013)
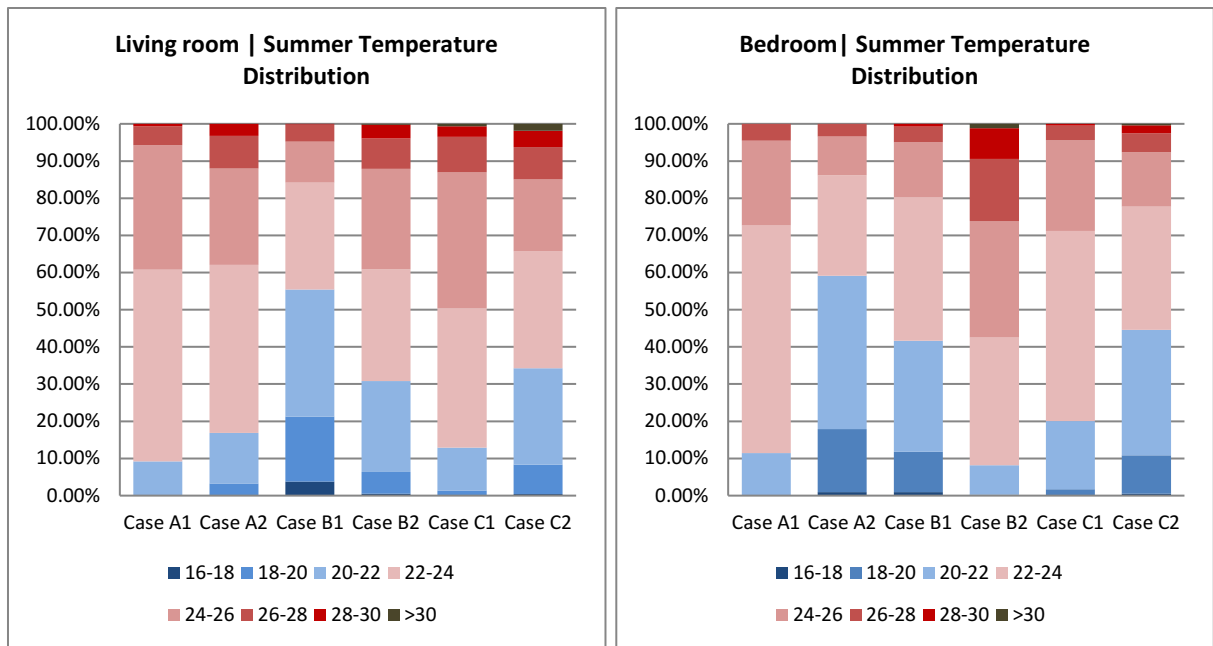
Figure 7 Temperature distributions in living rooms and bedrooms during the non-heating period (May-September 2013)

Figure 8 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 were recorded in Cases B1 and B2, often falling below the suggested EN15251 comfort levels of 20-26 °C (CEN, 2007). Case B1 had the lowest mean winter temperatures due to occupant's efforts to minimize their electricity bills by heating their house during the night only. Cases A1 and C1 had the highest winter temperatures as they kept their thermostats at around 25-27 °C throughout the day. Summer temperatures ranged between 21-26 °C in most cases, with the exception of Case C2 that presented 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 were due to prolonged window opening. High indoor temperatures were affecting internal relative humidity (RH) levels, which in general were 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. In the non-heating season both RH levels and temperatures increased, but remained inside the CIBSE recommended comfort limits of 40-70% (CIBSE, 2006).
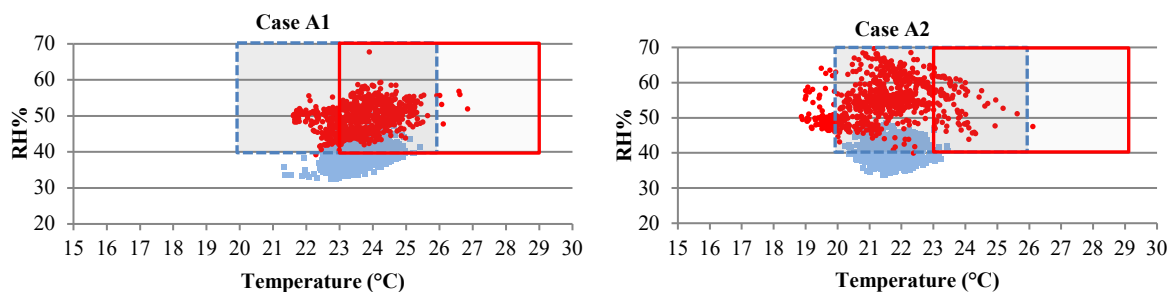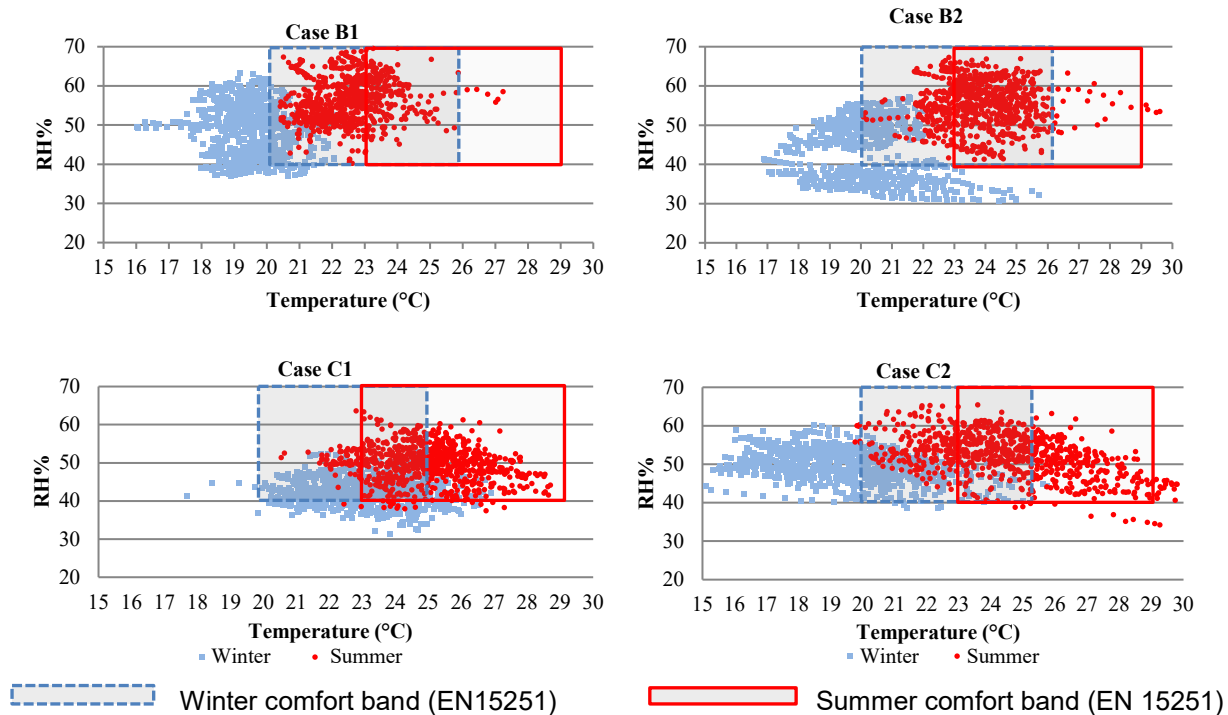
Figure 8 Average hourly temperature and relative humidity levels during winter (January) and summer (August).

Figures 9 and 10 show the average monthly temperature and RH in living rooms respectively. Average monthly temperatures ranged between 19-25 °C across all cases, with the lowest temperatures recorded in Cases B1 and C2. RH levels ranged between 25-60%, with the lowest levels recorded in Case A2 which also presented the highest temperatures during winter months (February-March).
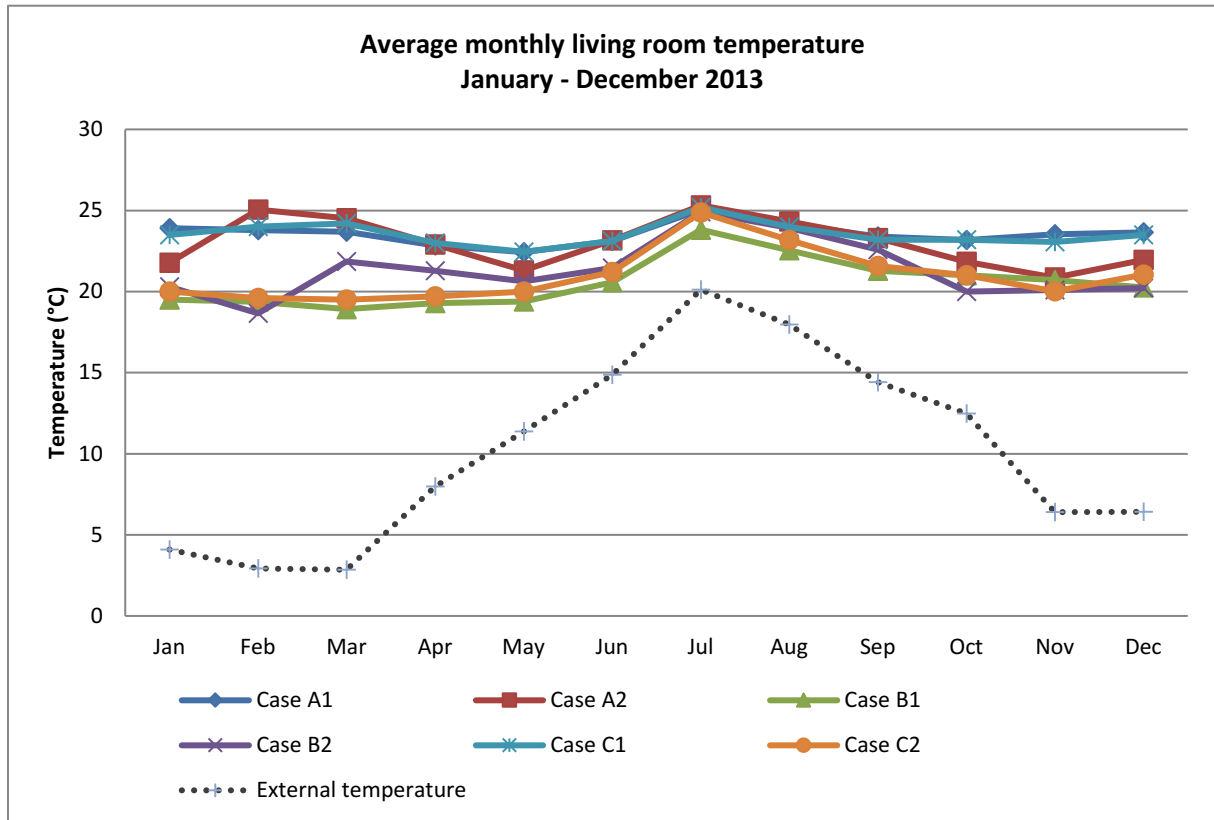
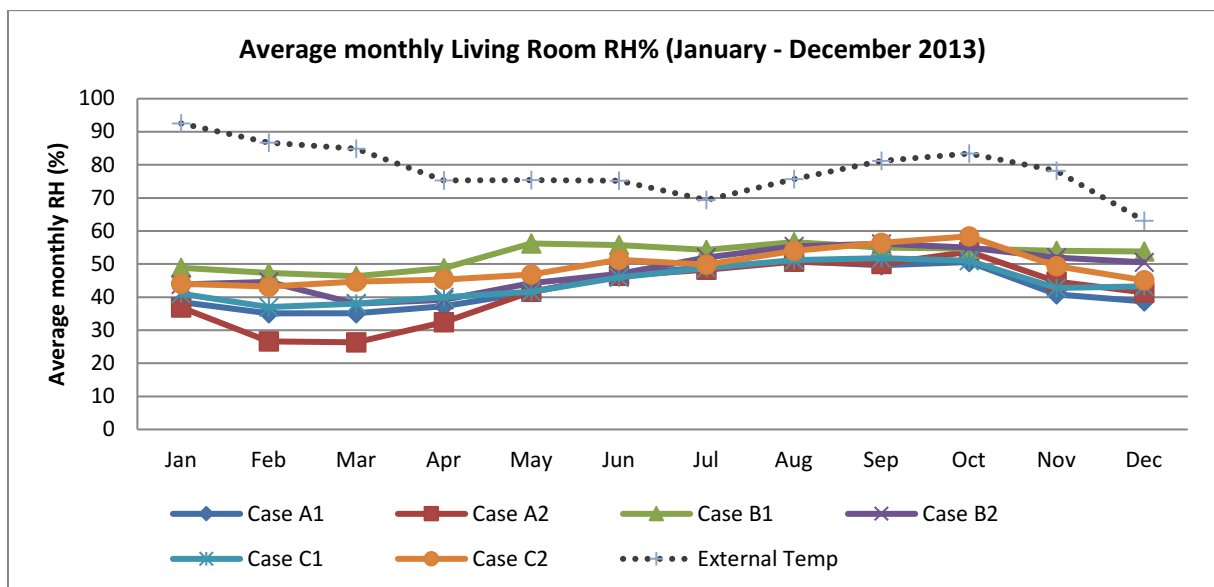*Figure 9 Average monthly living room temperature (January-December 2013)*

Figure 10 Average monthly RH in living rooms (January-December 2013)

Findings from occupant surveys and interviews helped to contextualise the environmental conditions in the houses. In Developments A and B, temperatures during winter were generally regarded as quite comfortable, whereas summer temperatures were perceived as slightly hot. In both developments occupants complained of poor control over heating with

some occupants feeling they could not control temperatures effectively. Complaints of high summer temperatures in Developments A and B indicated that the houses were not adaptable to warm weather conditions. This may have been 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 were perceived as comfortable from the majority of the occupants despite the fact that the two case studies from Development C presented the highest indoor temperatures across all six case studies. These findings indicated that the perception of comfort varied greatly between different occupants.

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 has been plotted against hourly average internal temperatures, as shown in Figure 11. During the heating season occupants in Cases A1 and A2 tended to keep their windows mostly closed and indoor hourly temperatures were kept steady throughout the day. Conversely, indoor temperatures in C1 and C2 presented a higher diurnal variation as occupants left their windows open for longer periods. While in C1 occupants tended to open the living room window and backdoor when indoor temperatures rose, in Case C2 occupants left the living room window open throughout the day. This habitual behaviour might explain the high energy usage of cases C1 and C2.
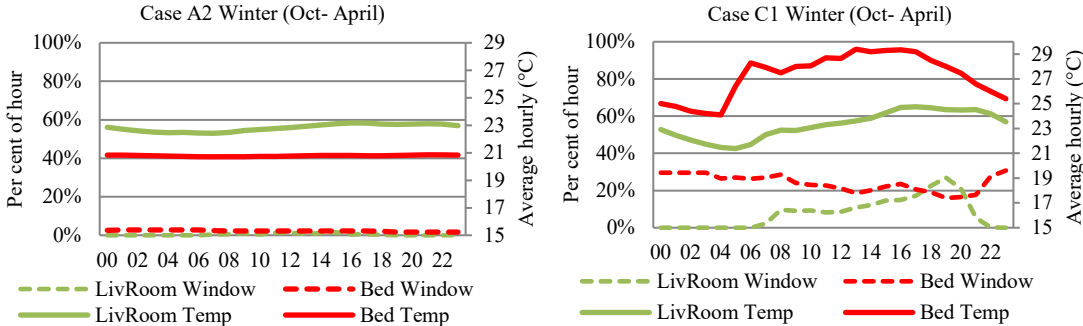

Figure 11 Hourly average temperatures and hourly percentage of window opening over a day

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 correlated well with human occupancy and human-generated pollutants and provided a useful indicator of relative levels of ventilation and indoor air quality. It is generally accepted that levels above 1000ppm 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 12. CO_2 levels during sleeping hours were much higher in C1 bedroom compared to A2 bedroom that had the same occupancy (2 adults) but was also less airtight. There appeared to be a correlation between the high CO_2 levels and window opening in Case C2, as occupants tended 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.
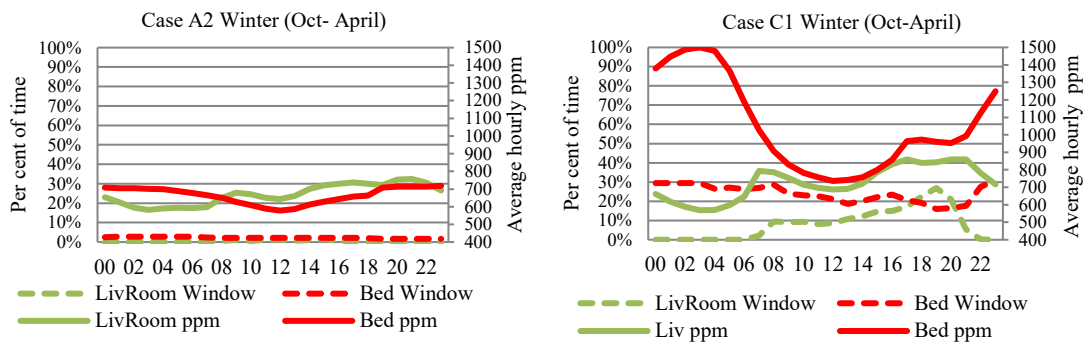
Figure 12 Hourly average CO₂ levels and hourly percentage of window opening across a day

The amount of time CO$_2$ levels were above the limit of 1000 ppm during a year in each of the four case study houses is graphed in Figure 13.
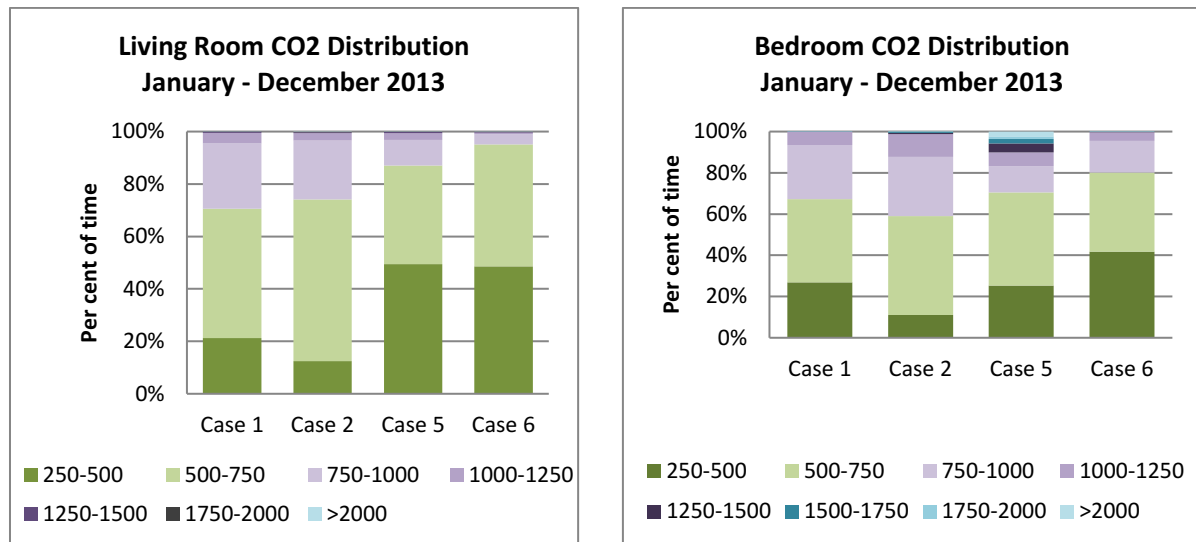

Figure 13 Distribution of CO$_2$ levels in living rooms and bedrooms (Jan - Dec 2013).

While in Cases A1 and A2, CO$_2$ levels in the living rooms ranged between 500-750 ppm for the majority of the time (50-60%); CO$_2$ levels were lower in Cases C1 and C2 living rooms remaining <500 ppm for 50% of the time. This was directly related to the window opening behaviour as occupants in Cases C1 and C2 habitually opened 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 exceeded 1000 ppm for 3-4% of the time, while bedroom CO$_2$ levels exceed 1000 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 were partly due to room occupancy levels (2 occupants per room during the night). The differences between living room and bedroom CO$_2$ levels implied that ventilation rates were not adequate when occupants were asleep (and opportunities for adaptive control were limited), particularly when the MVHR is not working properly.

Discussion

There is clear evidence that actual energy use and environmental performance of low energy social 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 was that most occupants were 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). More robust and effective ventilation strategies should be designed and integrated with the heating systems to 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 re-training 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 from the study 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 energy dwellings for achieving good levels of indoor air quality.

Conclusions

The study has not only highlighted issues of underperformance of fabric, services and systems in low energy social housing, but also shown how BPE-based approach can help to identify faults that would otherwise go unnoticed and become serious issues. With requirements for as-built performance likely to be included in future Building Regulations, the

importance of achieving real performance that matches predictions is becoming a mainstream issue (ZCH, 2013). Wider lessons are drawn from the study for policy makers, industry and academia:

- 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 (Gupta and Kotopouleas, 2018).

- 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.

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.

Acknowledgements

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[i] Standard Assessment Procedure (SAP) is the methodology used by the Government to assess and compare the energy and environmental performance of dwellings. Its purpose is to provide accurate and reliable assessments of dwelling energy performances that are needed to underpin energy and environmental policy initiatives. SAP works by assessing how much energy a dwelling will consume, when delivering a defined level of comfort and service provision. The assessment is based on standardised assumptions for occupancy and behaviour. This enables a like-for-like comparison of dwelling performance.

[ii] Air permeability is a measure of the air tightness of the building associated with the uncontrolled infiltration or loss of air through cracks and gaps in the building fabric. It is defined as air leakage rate per hour per square metre of envelope area at a test reference pressure differential across the building envelope of 50 Pascal. The test involves the pressurisation (or depressurisation) of the building by means of variable speed fan(s) installed to a suitable external opening while the remaining openings are closed and vents are shut or sealed. The resulting

difference between the external and internal pressure is used to calculate the permeability of the building envelope. Beyond the basic method, the test can be extended to include both pressurisation and depressurisation (in this case the final result is the average of the two values) and smoke test for the identification of air leakage pathways. In England, Wales and Northern Ireland the pressurisation testing of dwellings is a standard requirement of the Building Regulations since 2006 which currently set airtightness limit of 10 $m^3/h/m^2$@50 Pa, while in 2010 became mandatory also in Scotland.

[iii] Thermal transmittance measurements (W/m^2K) assess the effectiveness of specific elements of the building fabric as insulators. In-situ measurements are carried out with heat flux sensors that provide a direct measure of the heat flux from a surface through a construction element. The method, detailed in ISO 9869 [58], can be used to determine the U-value of individual construction materials or the U-value of building elements comprising several layers. Its value lies in providing data that enables investigative examination of a range of heat loss mechanisms and can be particularly useful if undertaken in conjunction with whole house heat loss measurement.

[iv] Infrared thermography is conducted using a handheld thermal camera which depicts the intensity of infrared radiation emitted by the surfaces and therefore the heat differential of objects in the view based on the materials emission values. The technique, is often used as a diagnostic tool to identify anomalies in construction which may be the result of gaps in insulation layers, different insulation characteristics, air movement within the structure, or more usually a combination of all three

[iii] Code for Sustainable Homes (CSH) is a voluntray UK national standard for rating and certifying the performance of new homes. CSH covers nine categories of sustainable design (Energy/CO_2 emissions; water; materials; surface water run-off; waste; pollution; health and well-being; management; ecology), within which points are awarded for good environmental practice. Points are converted into a six-point rating scale, where Level 3 is equivalent to building regulations, Levels 4 and 5 represent exceeding building regulations and Level 6 represents net zero CO_2 emissions.