Deep low-carbon refurbishment challenge: what hasn't worked as designed?

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Abstract

While Building Regulations standards become more stringent in order to meet ambitious UK Government reduction targets by 2050, low-carbon solutions in building stock refurbishment do not always perform as intended. Considering this, and given that there is still little evidence on deep refurbishments that implement low-carbon 'whole-house' approaches in the UK, this paper presents evidence on their implementation, installation and use, using a sample of 26 deep retrofitted social houses. The paper explores what has (or has not) been implemented as intended/designed, discussing the failures and successes that emerge under the lenses of effectiveness in delivery, performance, occupant satisfaction and control interaction with the low-carbon building system. Using an interdisciplinary approach, technical and non-technical factors are examined through a detailed analysis of the quantitative and qualitative empirical data. The overall performance in-use is discussed in relation to the initial refurbishment delivery goals. The findings reveal issues connected to knowledge, skills, communication and quality of installation of the low-carbon interventions and how these affect occupants' interaction and control behaviour. By recognising the importance to provide higher standards in installation of the new measures and improving quality controls in the implementation, the research outlines key messages and recommendations to different actors (i.e. policymakers, researchers, implementers, the supply chain and users) involved in social housing refurbishment programmes.

Introduction

In the UK's policy background improving the existing housing stock is one of the key targets. Current policy trends in housing refurbishments comprising regulatory or other low-carbon performance standards involve complex technologies, systems and innovative solutions to achieve the UK's demanding target of an 80% CO_2 reduction by 2050. In pursuit of the intermediate 2020 goals, the progress on social sector housing moves towards energy-savings measures, regulatory standards and emissions reductions approaches in refurbishment, associated with insulation measures, smart meters, 'Feed-in Tariffs', heating schemes and others, encouraging energy savings and low-carbon incentives. Nevertheless, the performance indicators for domestic refurbishments in general tend to rely heavily upon assumptions regarding the ideal behaviour of materials, combined systems installed to high standards under specific conditions, and ideal occupant behaviour in operating and interacting with them (Topouzi 2013). Against the backdrop of these initiatives is more than a decade that several studies on the UK's domestic energy use report that one of the major contributing factors on policies limited success in energy conservation targets lies 'in oversimplified policy analysis that has serious blind spots in the area of human behaviour' (Stern 1992 p. 1192) lacking of understanding how people interact with domestic technology (Lomas et al. 2006). Advocated also by other studies showing that too little attention has been paid to socio-demographic and cultural factors, which were generally found to have greater influence on how much energy is used in a household compared to the dwelling type or household structure (Randolph and Troy 2007). However, although a household's occupant behaviour is one of the key issues in building design optimisation, energy simulation and in-use performance evaluation approaches, there is also an argument that user behaviour can no longer be considered the only complex factor involved in explaining performance deficits (Gill et al. 2010).

The delivery of the national energy-use reduction plans is undermined significantly by the performance gap between designs' intended and actual performance, as energy consumption in housing is determined by several technical and non-technical interacting factors and aggregating effects. Since the 1970s, several studies from different disciplines and with interdisciplinary approaches have offered considerations and theoretical explanations in either of two correlated entities of social (demographic) and technical aspects in energy use. As is widely discussed elsewhere (e.g. Wingfield et al., 2008, Gupta, 2013, Zero Carbon Hub, 2014), to decrease the performance gap of houses energy use more integrated socio-technical holistic approaches need to be on the lead. On the other hand, to mitigate buildings' underperformance more evidence-based explorations of the interrelated factors are needed to feed into housing energy policies.

Methodological approach

The empirical sample presented in this paper involves 26 properties (out of 119) from a low-carbon 'whole- house' deep refurbishment of the UK Retrofit for the Future (RfF) demonstration programme, which was undertaken during my doctoral research. The RfF sample consists of low-rise social houses[1] spread around the UK. Two criteria were taken in consideration in the selection of the 26 properties in this study: the geographical location and the building type. Properties' locations, covering south east England, enabled comparison between cases with similar weather conditions using the same heating degree days. In this geographical area, three building types have been studied: semi-detached, end-terraces and mid-terraces.

The study employed an interdisciplinary approach to analyse complex interrelated technical and non-technical factors involved in occupants' interaction affecting in-use building performance. Engineering, social science-based and socio-technical theoretical approaches were combined. Different methods and techniques were also integrated to analyse the central phenomenon of interaction within three key areas: technical aspects (physical components of the building system), non-technical (household system of occupants/users) and the interactions of both (energy use and operation). The theoretical approaches selected by the study, including the user-centred theory, interactive adaptivity, practice theory and Science Technology and Society (STS) theory, have drawn attention and interpreter particular events of interaction on occupants' routinised practices. The methodological approaches involved thematic, classification, correlation and regression analysis, as well as triangulation to cross-check occupants' 'doings' and 'sayings'. The empirical data used consisted of qualitative data from in-depth semi-structured interviews and on-site technical and usage observations, as well as from long-term physical monitoring (gas, electricity meterings, temperature, humidity, CO_2) and in-situ spot checks. Tools from buildings science studies (building performance evaluation and post-occupancy evaluation) were used to capture and evaluate the distance between a building system's in-use performance and the design's intended performance.

Design intended and implementation goals

A 'whole-house' refurbishment approach was one of the priorities of the RfF demonstration programme. This approach intends that the household's needs (energy demand) and impact (carbon emissions) are seen as a whole. Although such approaches include a range of measures from cost-effective energy-saving schemes to renewable and low-carbon heating and electricity measures, as well as low-carbon improvements of the building fabric, there is no evidence yet showing how this 'whole-house' approach is able to deliver radical energy savings in practice involving the human factor (householders). At one end, the measures as placed today may define efficiency from a purely subjective policy perspective resting largely on their physical criteria; and opposed to arguments as such 'more efficient' does not mean lower energy use (Moezzi and Diamond 2005). At the other end, in the 'whole-house' approach the 'user' factor is neither clearly implied nor included in the current policy specifications. In this 'whole-house' approach, the measures (or both users) are described as 'passive' agents, with actual action (measures operation) but not interaction between them. However, even in the most passive design structures when the human factor is involved by definition a level of interaction is taking place.

TECHNICAL INTERVENTION

From a technical perspective, due to the diversity of building types and environments in the RfF sample and in order for each of them to be in line with achieving the energy and CO_2 targets, flexible guidelines on the technical requirements and specifications for all projects were provided by the Technology Strategy Board (TSB, now known as 'Innovate UK') (EST 2009). Space heating energy was not included in the specified targets, as this was considered strongly dependent on the overall level of intervention and measures installed in the property, although it was expected to be below 40 kWh/m^2/yr (Ruyssevelt 2011). Project applicants[2] for all cases were encouraged to calculate the proposed refurbishment interventions using the Standard Assessment Procedure (SAP) as the assessment method and/or a Passive House Planning Package (PHPP) for a performance simulation (TSB 2009). The key targets set out for assessment have been based on a reduction of 80 % from the 1990 figure and calculated with SAP 2005 and PHPP using the average baseline figures for an 80 m^2 semi-detached house (Ruyssevelt 2011; TSB 2009). They are compared to other mainstream high performance standards in Table 1. A large number of the applicants used AECB's Passivhaus technical standards in their energy design proposals (AECB 2007). The level of RfF targets as set out by TSB are in some respects between AECB's Passivhaus standard for the UK context levels and Building Regulations

1. The majority of the social housing units in the total RfF data sample are managed by non-profit housing associations and less than half by local authorities; in all cases, the social tenants meet allocation eligibility requirements before moving into the refurbished RfF properties.

2. 'Project applicants' refers to architects, building companies and organisations as well as housing associations.

offering design flexibility to adopt solutions based on different buildings' condition and needs (Table 2).

Design guidance was also provided through Energy Saving Trust publications giving technical guidance/specifications and design solutions and covering aspects for best practice refurbishment and high levels of energy-efficiency performance (e.g. EST 2009, 2010a, 2010b). These publications range from general 'whole-house' refurbishment guidelines to more specific systems such as heating systems, guides for airtightness and efficient ventilation, and micro-generation, as well as technical specifications and implementation guides for insulation, windows, lighting and other passive measures.

The level of refurbishment intervention

Two main clusters of building type emerged from the study's sample (n=26) based on similarities in terms of performance: the first group includes semi-detached and end-terrace properties and the second mid-terraces. These two clusters were also classified in terms of the level of intervention of the low-carbon improvements undertaken in *deep refurbishment* and *typical refurbishment*, as illustrated in Table 3. In most of the properties (n=19) deep refurbishment interventions were carried out, complying with Passivhaus standards (AECB 2007) and following BREEAM Ecohomes XB methods (Wilson and Dowlatabadi 2007). Figure 1 shows the level of the overall refurbishment intervention according to the low-carbon improvements undertaken in the 26 properties.

Despite the variation in the refurbishment interventions in the RfF sample, an outline of the low-carbon intervention strategies involved: design solutions for mains gas, electricity or both; space heating solutions from gas efficiency condensing boilers or micro combined heat and power (CHP) to heat pumps (HP) and other forms of micro-generation like biomass; solar technology for hot water heating and electricity generation for appliance usage, lighting etc.; natural or mechanical ventilation strategies with heat recovery and a combination of both; and other passive daylight strategies adopted by increasing window size or by integrating conservatory extensions into the building. Airtightness strategies and solutions to minimise thermal bridges also vary in the sample according to the special requirement for best practice in relation to the building's fabric. For all projects, innovative design solutions and combinations of measures and intelligent or conventional controls are included (Figure 1).

Building fabric

The insulation strategy involved a variety of design choices to achieve RfF performance goals for best practice of the five building construction types, i.e. masonry cavity (n=13), brick (n=5), concrete frame (n=4), mixed constructions (n=3) and

Table 1. The key RfF targets compared to AECB's high performance standards for building refurbishment.

Target	Primary energy consumption *(kWh/m²/yr)*	CO² emissions *(kg/m²/yr)*	Useful space heating energy *(kWh/m²/yr)*
SAP 2005 (for RfF competition)	*115*	*17*	*Not specified (expected <40)*
PHPP (for RfF competition)	*115*	*20*	*Not specified (expected < 40)*
AECB's Silver standard	*120*	*22*	*40*
AECB's Passivhaus standard	*120*	*No explicit limit (22–15)*	*15*
AECB's Passivhaus standard in a UK context	*78*	*15*	*15*

Table 2. England and Wales Building Regulations compared to the Passivhaus standard based on: Dowson et al. 2012: p. 302.

Building components	2010 Building Regulations Part L1A and Part L1B	German Passivhaus standard
Orientation and shading	*Not considered*	*Passive solar design principles*
Walls, roof and floor	*U-values of 0.25–0.3 W/m²*	*U-values of ≤ 0.15 W/m²*
Openings (windows and doors)	*U-values of 1.8–2.2 W/m²*	*U-values of ≤ 0.8–0.85 W/m² with solar coefficient of 0.5*
Air tightness	*Air change rate of 7-10 m³/m²h@50Pa*	*Air change rate < 1 m³/m2h@50Pa*
Whole-house heat recovery	*Not considered as buildings do not achieve air change rate below 3 m³/m²h@50 Pa*	*Efficiency of ≥ 75 % (Calculated according to the Passivhaus Institute methodology). Incoming fresh air pre-heated to > 5 °C*
Lighting and appliances	*Low energy lighting and A+ appliances*	*Low energy lighting and A++ appliances*
Total heating demand	*~ 55 kWh/m²/year*	*New build of ≤ 15 kWh/m²/year Retrofit of ≤ 25 kWh/m²/year*

Table 3. Classification of the level of refurbishment interventions in the RfF sample (n=26).

Level of intervention	Low-carbon improvements description	Standards and methods compliance
(DR) Deep Refurbishment (or deep retrofit)	Insulation (floor, wall, loft, windows), space and water heating system, daylighting, ventilation and space cooling, renewable energy generation, passive strategies, thermal bridges and airtightness strategies	AECB standards (Silver and Passivhaus), Eco-Homes methods
(TR) Typical Refurbishment (or typical retrofit)	Insulation (wall, loft, windows), space and water heating system, ventilation, lighting and airtightness strategies	Between AECB standards (Silver) and Approved Document L1B–Existing Dwellings Building

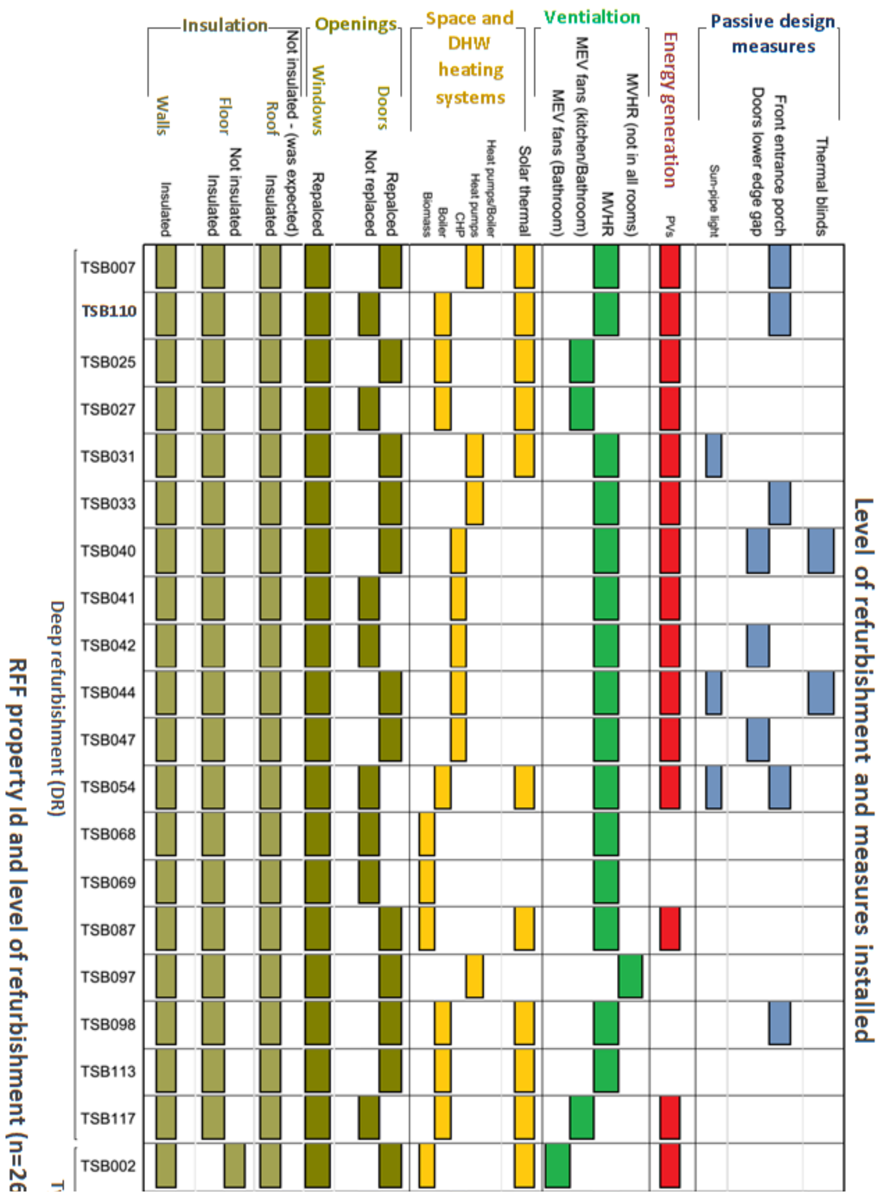

Figure 1. Low-carbon improvements and the level of refurbishment intervention in the RfF properties.

solid brick (n=1). In seven out of 26 cases, of which the majority wall construction was masonry cavity, wall insulation was to achieve a *U*-value above 0.2 W/m^2, fluctuating between Building Regulations and Passivhaus standards (see Table 2). In one of these cases – the solid brick construction type – it was even considerably higher than 0.3 W/m^2. In the rest of the cases, with the majority of them been insulated externally and different wall construction types, the insulation was to achieve a *U*-value equal or below 0.15 W/m^2 based on Passivhaus standards. As for other insulation measures, roof insulation in all properties was designed to achieve a value of 0.1 W/m^2 and floor insulation 0.15 W/m^2. As regards the openings (windows and doors), the majority of the properties (n=19) had the old windows replaced with triple glazing systems following the Passivhaus standards, whereas in the rest of the cases (n=7) high quality performance double glazing systems were installed. In the majority of these cases, windows' *U*-value was to Passivhaus standards at below 0.8 W/m^2. Only in seven cases were windows given a *U*-value between Building Regulations and Passivhaus standards, at above 1.1 W/m^2.

However, despite the competition requirements there are properties in the sample (seven of 26) in which the level of refurbishment is between typical and deep refurbishment (Table 2). The reason for this is that some of the measures (e.g. floor insulation strategies or door opening replacements) either were not considered in the intervention strategy by the design team or not finally implemented in the construction. Therefore, in seven properties although floor insulation was included in the design strategy it was not installed due to the extra time and cost involved. In 18 properties only the ground floor area or specific rooms on this floor level were insulated (e.g. living room, room extensions, etc.), whereas the suspended floor of the first level was not in any of the cases in the sample. Similarly the external doors have not always followed windows' standards in the sample (n=26) as the initial design intended. Therefore, in nine properties the old door system had not been replaced and in another four properties the external doors were replaced with those of a standard commercial quality.

REFURBISHMENT DELIVERY GOALS

Overall indoor air quality in the RfF properties considerably improved compared to previous conditions in all cases in the sample, with occupants generally being satisfied with post-refurbishment comfort levels. The improved building conditions affected occupants' adaptive behaviour for comfort, often resulting from rebound interactions. The interventions on the building fabric discussed above evaluated post-refurbishment in terms of thermal bridges and airtight strategies involving thermal imaging and airtightness tests. This has allowed possible insulation defects and air leaks to be located at the installation of the measures; the issues include missing insulation, condensation problems, etc.

Thermal imaging

The pre-refurbishment thermal images, in nine of the 26 cases, have contributed significantly in the design stage to detecting the main problems in the existing building fabric that needed intervention. Post-refurbishment, thermal imaging inspection has helped to evaluate the level of intervention and quality of installation works and detect defects in the building fabric interventions and construction failures in the insulation, opening installation and thermal bridges. These issues were examined within the three clusters of insulation type (external, internal and mixed insulation) to obtain a more comprehensive view of the factors affecting building fabric performance and evaluated along with airtightness tests and other building fabric characteristics.

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

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

In 16 properties, post-refurbishment thermal images have shown that fabric heat losses and air leakages have been reduced significantly compared to neighbouring properties. This is also demonstrated by the fact that in 14 properties examined the temperature of the tested wall surface is close to the external ambient temperature, with a difference of less than 2 °C. For the properties with external insulation, thermal imaging evaluation post-refurbishment shows that all buildings' air leakages and heat losses have significantly improved overall. Only in single case there are still present minor insulation defects on the party wall with next building, or cold bridge in the window seal. Major problems were detected only in one case in the sample (TSB076), involving cold bridges on wall edges and between walls and roof, as well as insulation defects on the walls, which was explained by the fact that no further insulation improvements were undertaken in this property by the RfF project on the walls as the insulation to Building Regulations standards was installed three years before the RfF project. In the majority of the properties insulated externally, the temperature difference is above 1 degree; only in one case (TSB102) are the internal and external temperatures at similar levels (Figure 2). For the cases with mixed insulation (internal and cavity fill or external and internal insulation), although the refurbishment interventions have generally improved previous building fabric problems, there are still some issues with the installation of the insulation, especially for the cases with mixed internal and cavity fill. Looking at the cases with internal insulation installed, the only defect identified in the thermal imaging is the cold bridge between the walls and ceiling, and in wall edges; the temperature difference falls similarly to equal to or less than 1 degree.

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

Airtightness tests

The design standard set by the RfF competition for all properties in the sample required air permeability based on the SAP calculations, setting a threshold of less than 7 m^3/h/m^2

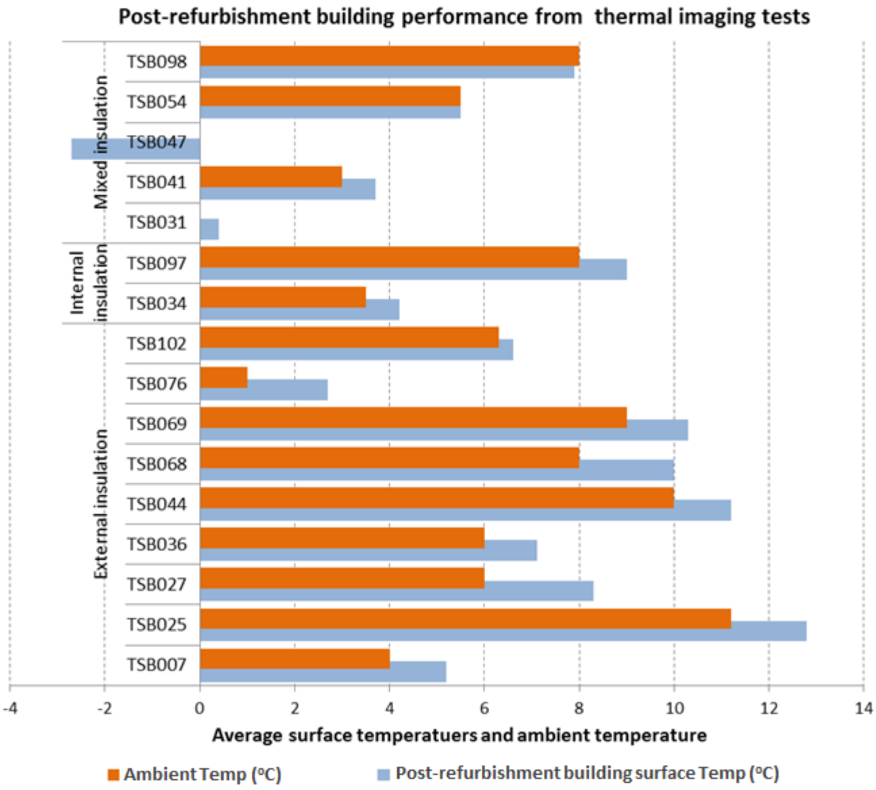

Figure 2. Comparison of the ambient temperature and buildings' fabric surface temperature in post-refurbishment thermal imaging tests.

@ 50 Pa. For almost all properties in the sample (25 of 26), the results from the actual pre-refurbishment airtightness test were compared with the post-refurbishment achieved after the low-carbon improvement work (Figure 3). The pre-refurbishment pressurisation tests showed that more than half of the properties (n=15) in the sample were below 10 $m^3/h/m^2$ @ 50Pa, whereas before low-carbon works only four properties were (somewhat surprisingly) already below SAP threshold airtightness levels. From the post-refurbishment tests it appears that airtightness design strategies succeeded in nine properties with high levels of airtightness before the works to show a significant drop of more than 50 % after refurbishment interventions. More specifically 18 cases are found below the SAP threshold, of which 11 have also achieved best practice levels.

Significant bias in the design intended and implementation was found in only two properties, in which the airtightness levels increased post-refurbishment levels compared to the pre-intervention works stage, by 45.6 % and 11 % respectively.

Looking at the airtightness levels together with thermal imaging tests and the low-carbon intervention measures undertaken in the fabric in these cases (n=11), it appears that their airtightness has not been affected by the type of the openings (windows and doors) or whether for instance the external door has not been replaced and the floor not insulated. However, the same levels of refurbishment interventions and high standard measures have been undertaken in the three cases with very low airtightness performance. In these cases this indicates construction failures, and clearly demonstrates that airtightness can be significantly improved not only by having a high standard of design or a number of high performance measures but most importantly by having a high standard of implementation in the construction and installation of these measures.

Evaluation of energy in use

The physical monitoring data for electricity (n=15 out of 26) and gas (11 out of 16) were evaluated. The modelled building performance, which was estimated using SAP and PHPP modelling approaches, was compared against the actual pre- and post-refurbishment performance. The comparison shows a significant gap between the estimated and actual electricity consumption. In almost all the cases (14 of 15), with TSB076 being the exception, the predicted consumption was lower than the actual values (Figure 4). There was fuel switching in six of 15 cases from previous gas boiler and electric storage heating systems to low-carbon systems. In eight out of 15 cases there was a considerably high increase in electricity use, with most properties (6 out of 8) often exceeding significantly both previous consumption and SAP estimated targets. In seven of these properties the excess electric consumption was despite the fact that gas continued be their main heating fuel post-refurbishment; and in two of these cases (TSB025 and 047) regardless of the photovoltaic (PVs) estimates generating 29.7 % kWh and 16.4 % kWh of their annual electricity consumption.

The electricity increase in some cases (e.g.TSB007 and 076) is explained by the shift from a gas boiler to an ASHP heating system and also by the failure of the MVHR performing to best practice standards due to installation faults. Or, in other cases like TSB102, despite the expected electricity reductions, in

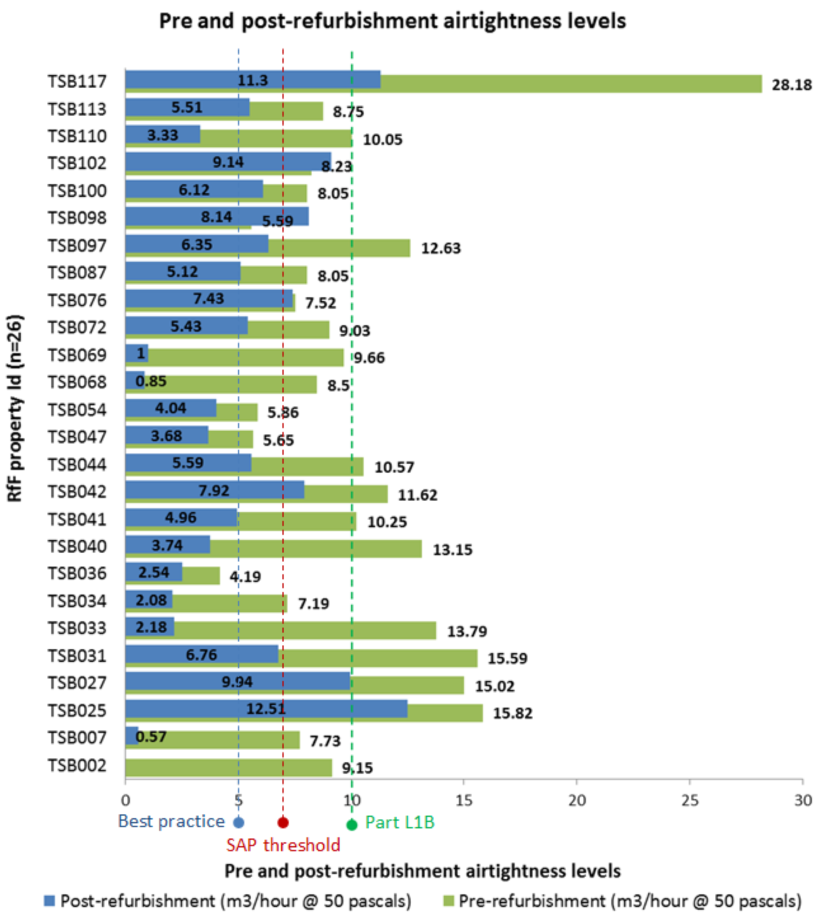

Figure 3. Airtightness levels in the pre- and post-refurbished properties (n=26).

switching from electricity to gas boiler occupants mixed energy behaviour post-refurbishment and frequently used additional electric heaters during the cold months, entailing the opposite results to those expected. Moreover, other factors like the extra number of occupants living temporarily in the property after works (e.g. TSB076, 034 and 102) need to be considered, as they often affected a household's energy-efficiency behaviour and routinised practices. In cases with a similar floor area per capita, no significant variations were found between the MVHR and MEV systems to solely account for the electricity increase. Lacking MVHR electric loads data, the study was not able to identify the extent to which the installation and performance issues that emerged from the sample have affected the total electrical consumption for each property. Delivery goals were achieved in seven of 15 cases with a drop of electrical consumption in the post-refurbished house compared to the previous situation of 11% to 53 %, in systems using the same heating fuel pre- and post-refurbishment (gas to gas) (four of seven cases); and even lower to 91 % to 45 % in cases with new low-carbon heating systems installed post-refurbishment (three of seven cases).

In the design strategies involving gas as a heating fuel the delivery goals achieved significant drops in gas consumption in the post-refurbishment stage, from 42 % to 90 % (Figure 5). For the cases with the same heating fuel pre- and post-refurbishment, this drop indicates a large improvement in their heating system efficiency. Although the gap between the estimated/modelled gas consumption is generally smaller, in six of 11 cases predicted is higher than actual consumption. Nevertheless, the figures for both gas and electricity indicate a failure of the modelling tools (SAP) to accurately estimate post-refurbishment building and systems performance.

The evaluation from the performance line calculation shows that there are also cases (e.g. TSB025, 110, 027 and 054) in which, although gas consumption decreased, the R^2 value at around 0.6 and below indicates a poor correlation between energy consumption and degree days. This also indicates either a rather poor heating control or the need for a larger quantity of data to be available for accurate analysis. Significant gas peaks, which do not follow indoor temperatures in other cases (e.g. TSB041, 117 and 110), were found also to confirm occupants' mentions of problems with the heating system. In this respect, malfunctioning of the system could also be a factor in the poor performance line results.

TECHNICAL ISSUES: DESIGN AND INSTALLATION PROBLEMS

The success of a 'whole-house' refurbishment approach is strongly dependent not only on the choice of energy-efficient design and low-carbon technological solutions but also equally on their implementation and installation. Occupants' heating post-installation experience was found to be strongly related to the level of control they had over the system, which was also

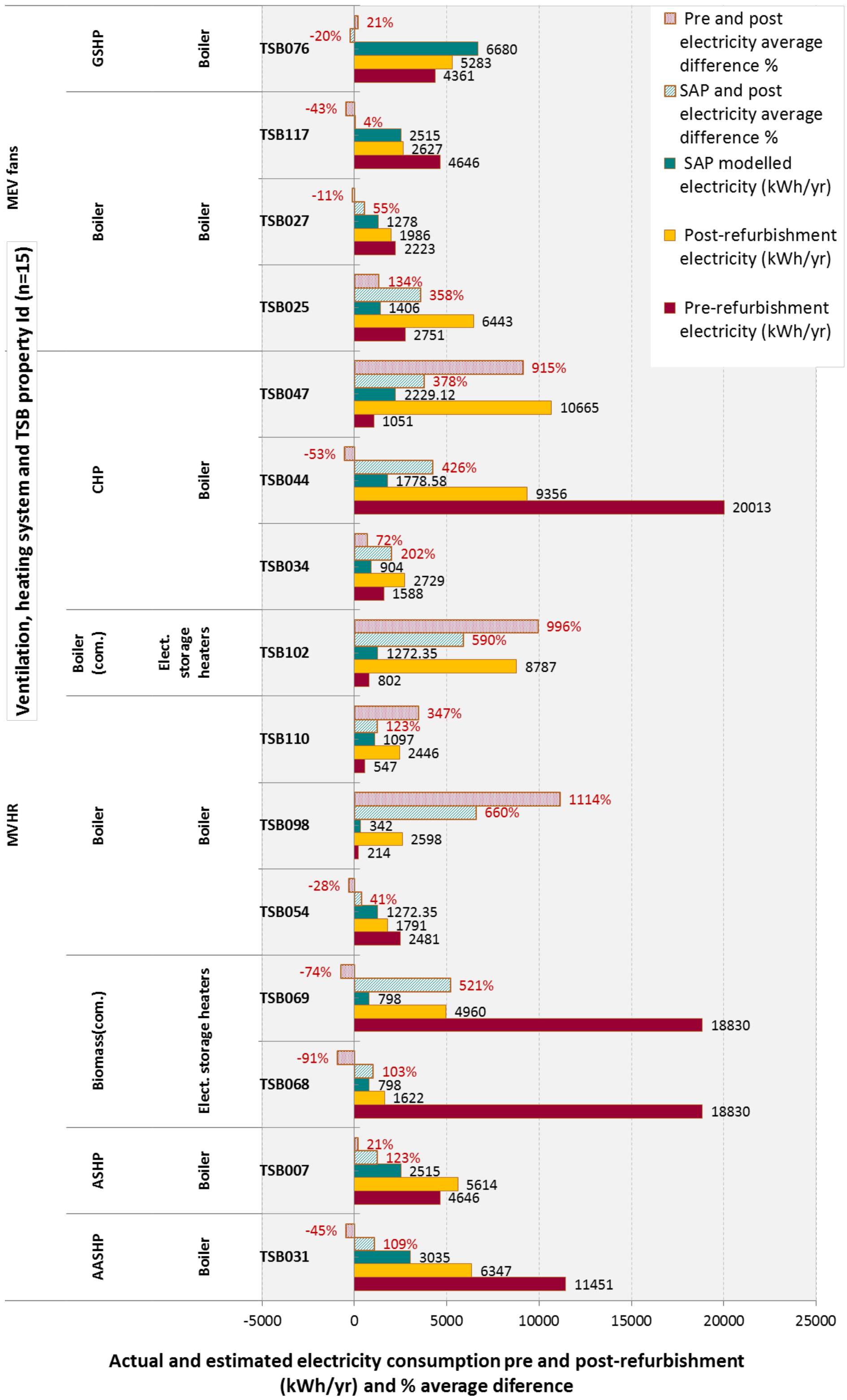

Figure 4. Comparison of actual and estimated/modelled electricity consumption pre- and post-refurbishment in relation to the heating and ventilation system (n=14).

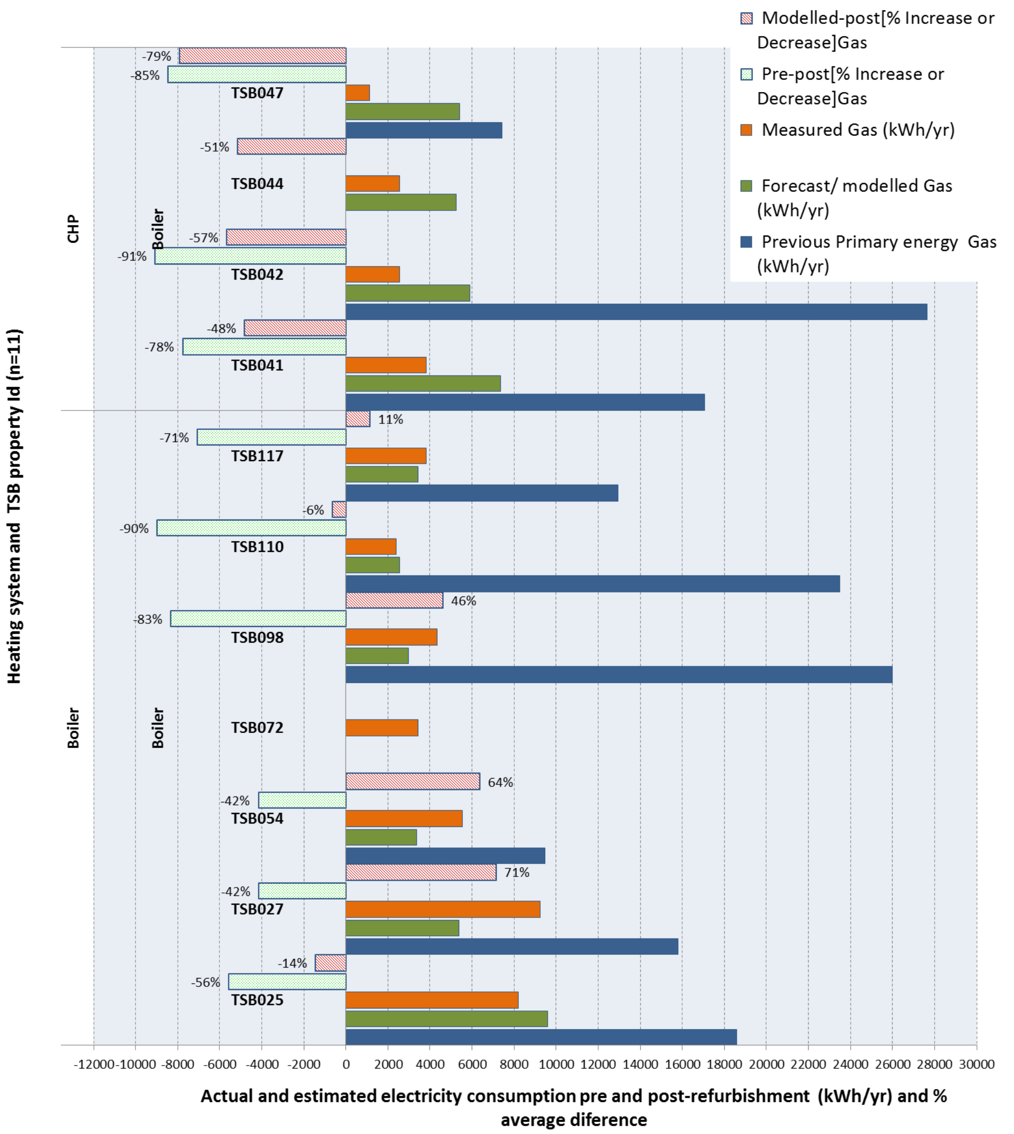

Figure 5. Comparison of actual and estimated/modelled gas consumption pre- and post-refurbishment.

found to be largely constrained by the malfunctioning of the low-carbon systems and their controls. The causes that may affect occupants' interaction and that highlight the key issues occupants reported or were captured by the post-occupancy evaluation survey are discussed in this section.

A common technical problem that clearly illustrates where a facet has not performed as designed or modelled was the lack of communication between the low-carbon heating systems and the intelligent heating controls (Wattbox), resulting in problems with both space heating and hot water. In four of seven cases with micro-CHP boilers in the sample this issue was reported as a problem of the sensors sending the wrong signal to the Wattbox and consequently the latter to the micro-CHP boiler. Therefore, in a case like TSB042 the mean indoor temperature was captured on the day of the interview at 19.4 °C when the Wattbox was showing room temperature at 40 °C, not allowing the proper function of the boiler to reflect occupants' comfort preferences. Similar system communication problems were found among GSHP, ASHP and the Wattbox intelligent controller.

An issue related to the automated feature of the Wattbox intelligent controller measure itself was reported as a malfunction. The innovative concept of the Wattbox controller is its design to switch heating ON and OFF, learning from a household's occupancy and occupants' behaviour relating to electricity and hot water usage. Its prefigured ability also does not require time clock settings by occupants. These are the issues that for some occupants entailed a lack of control over the measure. The fact that the measure requires a certain time (days) in this process of 'learning' occupants' preferences was the issue reported as a measure fault as it did not reflect their instantaneous preferences. The incapability of the system to respond to occupants' instantaneous settings has been a major problem in regard to setting up their comfort preferences. However, this issue has more to do with the automated options of the measure itself and the lack of information/training provided rather than a heating controls fault. Occupant TSB041 explains that the problem with the Wattbox controller compared to the standard programmer she used to have is:

… with this if you want the heating ON you press more heat it heats up but then it gets to certain temperature and clicks OFF but then it won't click back ON again … you have to keep pressing every time … (Occup. TSB041).

The problem in other cases like TSB100 is that when occupancy varies it is difficult for the intelligent control to understand occupants' preferences and occupancy slots to be adjusted as access to Wattbox advanced control settings to set up their occupancy schedules was locked for users.

Other failures reported included extreme temperatures in the water tank followed by high levels of noise in the CHP boiler unit or installation leakages. In other cases like TSB076, the GSHP system has never worked properly due to serious installation faults affecting the heat pump (insufficient depth of the horizontal loop system to reach ground temperatures and provide high collection efficiency). Furthermore, in the properties with a shared biomass boiler (TSB068 and 069) occupants reported problems with the system when their demands for space heating and hot water ran concurrently in the two houses:

… I think because it's controlled [biomass boiler] by both the houses, I think that if we put the heating ON at the same time or they have a bath at the same time … cause that's the only time we've had a problem with it … (Occup. TSB068).

Installation problems were found in the thermal blinds (e.g. TSB044) that resulted in the measure not being operated completely, as in all windows the blinds were glued into the mounted top and fell every time occupants tried to use them. Also, monitoring systems like the Green Energy Options Trio display had different operational problems in all four properties they were installed in. In the case of TSB098, the occupant explains that the system never worked as she was told that it was still being updated and although she was told that someone would come back to explain the system and put it in operation this never happened. In comparison, in case TSB054 the issue was not only that the monitoring display never worked but also that it was installed at a height that constrained any interaction with the user anyway.

Design issues relating to the measures installed were found in both mechanical ventilation systems and natural ventilation. One of the problems captured very often was that the MEV extractors in the wet rooms (kitchen and bathroom) had one joined switcher with the light; in other cases, although it was in a separate switcher it was placed at the top edge of the wall or ceiling, causing a constraint due to its height. As for design choices with an impact on users' practices, in many cases the cooking extractor fan was installed to recirculate air inside instead of releasing it through an outside vent to extract moisture and odours outside, while in other cases it was not installed at all, relying only on the operation of the MVHR.

In properties with mechanical ventilation systems (MVHR) and controls a common problem in some of the properties (four of 21) with the MVHR was that the system was blowing cold air during the cold months and freezing cold in warm months:

… where all is ever done was to blow cold air … so in the winter I closed them. I leave open just a little bit to avoid condensation coming back … but they don't work in the winter; they blow cold in … which is lovely in the summer as you get the breeze … [When she asked about this] … they [the installer and technicians] all tell different stories … I complained because it was cold in the bedrooms and the guy which the company was [MVHR installer] said that it was never intended to blow warm air; it was only intended to bring fresh air in, not to circulate hot air anyway, whereas these heating people told me that what it was … I never actually got the right answer … (Occup. TSB087).

In natural ventilation the most common design issue that emerged from the sample related to the operational problems due to the location of the kitchen window and the increased width of the wall to achieve insulation standards. Thus, in 15 cases out of 26 cases occupants could not open the window above the sink because they could not reach it. As occupant TSB047 explains:

… I can't reach it unless I step on a stool step … [before refurbishment] it was nearer – this is wider, see … I have a little stool but I open the door [to move the steam out] (Occup. TSB047).

The size of the windows and doors installed has also been a design choice that in some cases (e.g. TSB036 and 054) significantly affected occupants' interaction with the measure and consequently ventilation practices. Therefore, in the case of TSB036 the big sizes of the bedroom window and window door cause them to occupy a great space in the room, leaving very limited space for occupants' activities. In TSB054, the change of the window type from a small tilt pane to a pivot/tilt one has increased difficulty in operation. Occupants in this case cannot have full operation of the window due to its increased weight (one pane is triple glazed) and also because of the low sill plate, which creates safety issues around falling out when occupants try to fully pivot the pane. Installation and design faults also prevent occupants from fully opening the kitchen and hallway windows in the cases of TSB047 and 110 (Topouzi, 2013).

Other measures installed for natural ventilation have not always allowed users' interaction. For example, the skylight roof windows installed for manual operation by using a telescopic pole has also been problematic due to the height and weight of the triple glazed window. Or, in case TSB087, occupants cannot interact with the windows' trickle vents because they were all sealed, as the occupant explains:

… [the windows' trickle vents] are all sealed. [The project team] have all sealed them up cause he failed his first [airtight test] … after the works; they [did] a test and it failed, they didn't [have] the rating they wanted so … he went around and masticed all the vents … so in all windows all the vents are sealed … (Occup. TSB087).

Other installation issues and measure defects were found in the case of TSB034, in which occupants reported condensation between all window panes when the external temperature drops. This may indicate faults in the sealing process of the windows and the poor quality of the double glazed windows installed. As well as installation faults affecting the external doors in some of the refurbished properties (n=3), had as a result projects failing the airtightness tests (levels above best practice standards in Figure 3) due to significant draughts:

> … in our front door there was a gap that I could literally fit my hand in … (Occup. TSB031).

Passive measures in natural ventilation like doors' lower edge gap in the case of TSB042 were built up bigger than designed, resulting, as the occupant explained, in significant heat losses in the living room from the unheated entrance hall and stair space.

NON-TECHNICAL ISSUES: USER INTEGRATION

The intent in the whole-house approach was also to include a systematic handover process that would provide to occupants the necessary information on the level of intervention and introduce the low-carbon measures, systems and controls installed in their properties post-refurbishment. This process was broadly specified by the competition, however, leaving mainly to project applicants the choice of type, time and key person to provide the handover approach and training/demonstration of the low-carbon building to occupants. One of the key factors affecting occupants' opinions and their interaction with the installed low-carbon systems and measures was the level of training and demonstration provided. Except for the properties with a gas boiler as the heating system, the households had to interact without having any previous experience or tacit knowledge of the new innovative heating and ventilation low-carbon technologies and intelligent controls in the RfF properties.

Training provided on the systems

The main variables in occupants' introduction to the measures are: the time that the instruction or training took place, the type, and the person(s) who provided it. In the pre-refurbishment stage only seven out of 26 households had an introduction and wash-up meetings with the project team, low-carbon system agents and other RfF residents. This involved the conveying of basic information about the scale of the low-carbon and Passivhaus refurbishments and about the measures and systems whose installation was planned. The information in this introductory stage varied from vague discussion on eco-friendly houses to more specific information for the measures and technologies incorporated into the RfF refurbishment (e.g. insulation type, glazing and heating systems, etc.). In just a couple of cases were occupants also informed about energy-saving lifestyle issues. Although this may have helped some of the occupants to understand the scale and type of intervention, in some other instances the information was found to be overwhelming and at times confusing. For instance, in case TSB042 occupants had attended meetings with other RfF residents but, although they were satisfied with the information on solar panels and the glazing systems, they also thought that:

> … there was lot of stuff that were talking about that they didn't really apply to us, but there were several people representing different companies … (Occ. TSB042).

Training/instructions timing

Regarding the time the training occurred three main groups emerged from the sample: during works, after completion of the works, and a few months after occupants had started living in the RfF property. In the majority of the cases (n=17) the hand-out and information was generally provided on the completion of the refurbishment. For the households that had not been relocated during works only three cases out of eight had an introduction to the measures during the works. Although it would be expected that for the households that lived in the property it would have been more straightforward to get information and a demonstration of all the measures' installed controls during the refurbishment, only one case (TSB087) had a demonstration of the heating systems controls. In this case the depth of the information was clearly a consequence of occupants' personal interest and proactivity to research and ask about the installed measures. The good rapport they built with the project team and technicians allowed them to have a better level of training and demonstrations several times during works:

> … only really basic stuff [instructions/training] … I mean I was here [in the property during works] for most of the time so I learned a lot from the guys that were putting in [systems installation] because I like to watch what they were doing and I used to ask questions. So did my son and that was really helpful … as for the end of it I've got a manual for the boiler … there was no instruction for [the solar panel] because it's going to do its job anyway … (Occ. TSB087).

The timing of the instructions provided to the occupants was crucial as information provided too early or too late was found to not be well received or add to occupants' understanding of the new systems and controls. The introduction process, conducted immediately after they moved in, for cases like TSB072 was rather overwhelming for occupants in terms of remembering and understanding the demonstration of each measure installed. This demonstration was provided by different people in a one-off visit and the occupants had not had any previous interaction with the systems. In a few cases (n=4), occupants had been merely introduced to some but not to all measures installed whereas training was delayed for up to seven months after completion of the works. In other cases (e.g. TSB042, 036 and 110), occupants were still expecting measures to be explained and someone to train or provide them with other types of information for the combined systems installed, which was clearly not the intended RfF competition's handover process:

> … we were supposed to receive a booklet manual with instructions on how we needed to operate them [heating and ventilation system] but we've never received it … (Occ. TSB036).

Type of information

The type of information varied in the sample from a quick demonstration to a single-page leaflet or booklet with very broad information on energy issues, and not always on the controls of the measures installed. Three main types of instructions were found in the sample: basic oral information on the systems, general instruction leaflets on the measures (or an introductory hand-out booklet) and technical specification manuals of the systems/measures installed in the RfF properties. These types were often combined or followed by a visual demonstration of the system controls. In a large number of cases (eight out of 26) occupants had merely oral information on the new low-carbon systems. Only two of those households also received a demonstration of some systems' controls. An instruction leaflet with general information on the measures and an introduction booklet for the RfF low-carbon house were the only types of information provided to the occupants in other households (n=2). Furthermore, only in nine out of 26 properties was basic oral information combined with leaflets containing general instructions on how to use some of the intelligent heating controls:

> … one A4 for the Wattbox [instructions leaflet for heating control] … I don't know how to work it. Well, basically on the Wattbox it says ON/OFF and that's it so that's what I rely on … (Occ. TSB042).

In other cases like in TSB040 and 033 the leaflet provided information on energy-efficient behaviour, i.e. how occupants could change their practices to maximise energy benefits and savings. This dealt mainly with issues like the amount of water when boiling a kettle, etc., but not on the measures installed in the RfF property. Information about the refurbishment of the systems/measures installed together with suggestions for energy-efficient behaviour was provided in a hand-out booklet in other cases. However, it appears that in the majority of cases occupants found the booklet information too detailed or long and so they did not read it:

> … the manual [house booklet] explains the main "ethos" and concept of the eco-house, for example if you make a hole in the wall you need to [seal] it because of the insulation … (Occ. TSB033).

Occupants' interest in measures' controls was constrained significantly by the type of information when they were left with technical specifications manuals for installation and maintenance of the systems, and many of those not even in English (n=7 cases). Clearly the content of the manuals was much too technical for people with no technical background or expertise on such combined systems:

> … we've been left with a manual of the boiler instructions and the shower instructions … [Are they easy to understand?] Not for a normal person. I think if you obviously know about boilers and things you would understand it … but for the average person no, not really … (Occ. TSB025).

Person(s) providing the information

The key person(s) providing the information also played a significant role in occupants' experience with new systems and measures' controls. The main people involved in the instruction/training process were a person from the housing association or council, the project team (e.g. project manager, architect, etc.) or the installer of a specific aspect. However, the constraints have not always lain with who was providing the information to the occupants but to a great extent in the knowledge that this person had to offer on the systems and measures installed, as well as on the rapport occupants had with this key person. The person involved in the training in 13 cases was someone from the local authority or housing association ('housing officer'), who in most of the cases was not aware of the systems and did not have the technical expertise to introduce and train occupants on the specific measures. This aspect may explain why in 12 out of 13 cases in which the key person for training was someone from the housing association or council occupants had no demonstration of measures' controls.

Occupants that received information on the measures from the project team and system installers also reported issues related to lack of knowledge and expertise on the specific low-carbon systems. Therefore, there are cases like TSB033, where occupants who experienced a problem with the ASHP boiler explain that:

> … the people who came to repair [the ASHP boiler] had no idea how to switch that boiler properly … you begin to think … did they ever have a test round with the boiler? … even the person who came for the boiler didn't know about the Wattbox [heating controls] … (Occ. TSB033).

In other cases (e.g.TSB87) occupants report having a very mixed understanding of the purpose of the biomass system and controls as different people gave them different instructions. In case TSB100, occupants had to discover for themselves different practices to fix problems with their CHP boiler like rebooting it, as neither the engineer nor the technician knew how to fix the problem.

> [the CHP technician] is self-taught because the he came and he didn't know how to do it [fix CHP boiler], he was reading the manual … I don't want to touch it because it's expensive as well … the only thing we do is to reset it when it's not coming ON … [occupant demonstrates how she/he resets the boiler] (Occ. TSB100).

Another issue that came up from the interviews in the majority of the cases was that people on the project team, site management, contractors or installers of the measures were often changing due to redundancy or companies' liquidation issues. This had a significant impact on the level of introduction to the measures, as the key person(s) conducting occupants' training was often unaware of the measures and systems installed in the RfF property.

To a large extent (14 out of 26), occupants were dissatisfied overall with the level of training they received on the new systems. In five cases, occupants were neutral about the training process, feeling that they had not received enough instructions and that they would prefer a measure-by-measure visual demonstration of each system and measure installed. This has been a serious limitation of the training process as only in 10 cases out of 26 did occupants have a demonstration of some (indeed, not always all) of the systems installed in the property. In this context, occupants' main requirement in all cases, which the RfF competition specifications failed to provide them, was a measure-by-measure visual demonstration from an expert on all the measures/systems installed in their property in the first weeks after they moved in. Although measures' demonstration was an initial prerequisite for the RfF competition, the demonstration process was not specified and no specific guidelines provided, as a result it was not employed in all cases in the sample sufficiently.

Discussion of key factors affecting deep refurbishments

From the above it is clear that the success of a whole-house refurbishment approach is strongly dependent not only on the choice of energy-efficient design and low-carbon technological solutions but also equally on their implementation and installation.

In regard to the design, the insights show a more critical approach needs also to consider other factors before offering one solution and set of technologies to fit all refurbishment cases. Strategies like Passivhaus standards can be, for instance, the most appropriate for airtight performance specifications, but factors like location, occupants' cultural habits and ventilation practices need to be considered in the design choices in relation to the MVHR system and windows. A critical approach to MVHR, for example, should have considering that window opening in urban locations is often constrained by privacy, noise and security factors, whereas the performance of MVHR in rural areas was found to be compromised, performance wise, by occupants' routinised practices of opening windows to ventilate their house. Design solutions need to take a more occupant-centred approach that also considers social housing occupants' lifestyle and family needs, integrating these aspects into a whole-house refurbishment approach and low-carbon design choices (e.g. MVHR system and smoking habits, biomass and manual feeding, lack of storage space and low-carbon equipment, etc.). In natural ventilation, design faults constrain windows' operation due to the increased wall thickness and sill height. Issues related to the usage of the measures need be addressed early in the design process and to consider different types of windows, handles and opening side location, etc.

An important finding was that occupants are active in consciously regulating heating controls, repeating previous practices when operation is not prefigured or coming up with their own alternative solutions to adaptive technologies' design limitations. This clearly implies that some heating practices are robust against major changes in the building and heating system context, with obvious implications for the design of such controls. Occupants' interaction with intelligent controls like Wattbox designed to automatically detect and learn occupants' comfort preferences from their routine repetition provided insights into the mainstream user control experience with a technology that has as its main goal the provision of maximum efficiency, comfort and ease-of-use by 'ensuring' that the user only "uses the energy when and where they need it" (AlertMe 2011). The study argues that heating control technologies as such need to still offer the option of user interaction and control when this is desired, thus being more adaptive to occupants' immediate needs. This echoes previous studies' conclusions that adaptive intelligent technologies' design may offer advanced functionalities but still need to leave a window for user 'manageability' and operation (Yang and Newman 2013).

The refurbishment timeline and management of the works had a significant negative impact in the households living in the property or relocated during works. In all these cases the refurbishment process took much longer than estimated. The initial intention of the RfF project for room-by-room refurbishment was not as successful as planned in any of the cases examined. One of the factors that was difficult to plan and incorporate successfully into the refurbishment works' order was the diversity of occupants' patterns of everyday life in every household. This was largely dependent on occupants' level of engagement with the process, the project information provided and communicated before and during refurbishment, and their rapport with the project team and constructors. Project delay affected in some of these cases (e.g. TSB117) the quality or completion of works, which was compromised by the rush to finish the project.

Installation problems in several combined systems were found to be affecting comfort and occupants' interaction with them, whether these were between low-carbon technologies and conventional systems (e.g. gas boiler and solar thermal system) or in the communication between low-carbon systems and intelligent controls (e.g. CHP and Wattbox controller). It may have been possible to avoid problems with user controls, system and design faults if the building system as a whole had been tested thoroughly by the project team before and after works completion, and better support given to occupants when occupied. Lack of skills and building expertise (e.g. on the part of building teams and installers and other people involved in the project) on the installation of the specific low-carbon measures and combined systems (e.g. a system of the CHP boiler and solar thermal measures controlled by Wattbox) has been one of the main failures to achieve systems' best practice performance. Occupants' mixed understanding and confusion regarding the new measures installed was often the result of the many different opinions on system controls proffered by different people involved with the project.

Lack of knowledge of the specific low-carbon measures by the project teams and the people involved from the housing associations and councils ('housing officers') suggests not only that there is scope for skills improvement but also that there is a role for one key person in engaging and communicating information to the occupants, to act as project lead or liaison with the experts, providing demonstrations and training to support existing occupants on the specific measures installed and to train future occupants. Technical specification manuals, booklets, leaflets and different written material proved to be too technical and not always easy to use. The information needs to be communicated in a simple way, not only via oral information about the refurbishment's interventions and systems installed (whether conventional or intelligent) but also through a visual demonstration of the controls. The use of different formats like images and audio-visual material that communicates information in occupants' languages could contribute more effectively to users' understanding. Information at the pre-refurbishment stage can contribute to a better understanding of the scale of the intervention. This should be focused on introducing to the occupants the specific systems and measures designed for installation in the project. The instructions/demonstration provided post-refurbishment need to be well organised and structured, following a measure-by-measure approach within a month after occupants move into the new property (neither too early nor too late), to allow them sufficient time to 'digest', interact and familiarise themselves with the new systems and measures. Despite occupants' expectations and consent to live with the energy monitoring equipment, there was generally a lack of feedback on their energy consumption and interaction with the new measures. Monitoring systems like Microwatt may have been installed but never worked to provide occupants with feedback on their energy use and the new measures installed.

Conclusions and recommendations

The evidence has shown that users' control behaviour is not the only factor affecting in-use performance and that the extent to which the performance gap is either increased or decreased depends on the effective implementation of high standards in the design and installation at the delivery stage. An outline of recommendations regarding the main key issues that have emerged from this study is given below.

RECOMMENDATIONS FOR POLICY MAKERS

The barrier to short- and long-term policy visions, action programmes, regulations and standards that involve energy-efficiency improvements in vulnerable low-income households and hard-to-treat properties in social housing still remains critical at the level of interpretation, implementation and degree of effectiveness. The targeted energy reduction policies in these groups can be more effective, as economic-related energy cost factors and improved building environments are found to be strong motivators for occupants' behavioural change and energy awareness increase, especially when feedback processes are involved. Mass low-carbon intervention programmes would need to incentivise different stages of aftercare support at the post-construction stage. This would include monitoring reviews and feedback processes *to* and *from* the users, from the initial occupancy period and up to the first two years of the building in-use, using POE and BPE processes. The use of this reciprocal feedback approach *to* and *from* the user is crucial first for the users to understand the effect that their practices and interaction with the building system have on energy use and second for policy makers to evaluate the degree of effectiveness and implementation of such low-carbon schemes from evidence-based feedback on in-use performance.

Technical problems and installation faults that emerged from the design to construction stages are found to significantly affect a building's in-use performance and occupants' interaction with the new low-carbon interventions. Incentivise mandatory quality controls at post-refurbishment stage like the BSRIA (2014) Soft Landings (SL) guidance approach, in which quality controls and 'reality checks' before the building handover and occupants' actual use are conducted. Also to be recommended are mandatory diagnostic building evaluation and tests at the pre-refurbishment stage on technical issues related to the building system and non-technical aspects of the household system, which could inform and integrate early at the design stage low-carbon intervention design choices that fit better to users.

The loss of knowledge between the design, construction (implementation/installation) and in-use stages, the lack of communication between (and within) the different sectors and the ways knowledge is disseminated to a building's users also have a significant impact on buildings' energy performance gap problem. Other communication channels such as an evidence base on 'Bank of Failures' and 'Successes' from different low-carbon refurbishment trials in the UK should be incentivised. In this, 'horror' and 'hero stories' would need to be treated the same in order to have an effective impact on the low-carbon buildings' learning curve. 'Horror' stories (Janda and Topouzi 2013) are often drowning in the loss of knowledge holding back approaches like 'learning from our mistakes'. A 'bank' as such could provide different sectors (policy makers, research supply/building industry and building users) with valuable lessons from past experiences to help avoid repetition of the same failures.

In 'whole-house' deep refurbishments complex low-carbon systems and combinations of measures were often found to underperform due to installation failures as a result of multiple skills deficiencies in the current building professions. Meeting the low-carbon skills challenge requires incentives not only for improving the building expertise on single technological innovations but to create new structures of multi-skill professions with the knowledge to support combined systems and 'whole-house' intervention approaches. An innovation curve should be incentivised, in which the current rigid boundaries of traditional professions would not just move towards single skills expertise but toward combined low-carbon services that could support current challenging best practice performance standards.

RECOMMENDATIONS FOR HOUSE PROVIDERS

Deficiencies in the handover and a lack of aftercare support for refurbished low-carbon buildings in regard to the existing approaches was found to result in major problems in buildings' operation, maintenance and energy-use performance for both users/occupants and social housing providers. Occupants' handover and training/demonstration on the installed measures from a high skilled person several times after occupancy needs to be ensured. Different stages that handover information and training could take place are as follows: Stage 1 – early pre-handover (pre-refurbishment) introduction of the building system and design solutions proposed. This stage would ensure that occupants/users' lifestyle and family needs comply with the proposed low-carbon interventions. Simple visual material or leaflets with basic technical information on the proposed measures are introduced; Stage 2 – Handover (on-site) in the first few weeks of occupancy, providing measure-by-measure visual demonstrations. Occupants would be left with audio-visual material with systems/controls' demonstration of their own house or with a simple visual manual that explains step-by-step the combined systems/controls operation (repetition of Stage 2 demonstration process after six months); Stage 3 – aftercare service and maintenance that involves on-site checking of systems and measures' mal-operation following informal chats with the occupants to identify interactions that may affect performance (repetition of Stage 3 operation check and feedback reviews every year, preferably during heating season). A contact list for technical support for each measure or combined systems would also be provided and updated every year during the Stage 3 visit. The key person ('housing officer') assigned for the specific houses need to be well trained on the specific measures installed, as well as able to deliver visual demonstrations from expertise on operation after 'reality checks' and before the occupants' handover.

RECOMMENDATIONS FOR THE SUPPLY CHAIN AND BUILDING INDUSTRY

High performance standards in deep refurbishments include complex combined systems and controls that require particularly high specifications at the construction stage. However, installation failures were found to decrease best practice performance and increase the operational complexities of occupants' interactions with building systems at the in-use stage. Design solutions need to be kept simple and well communicated by the design team to the project team (project manager, contractors, technicians, installers, etc.), thus providing adequate knowledge on the combined low-carbon systems and controls proposed. The project manager needs to have a key role from the design development to the final pre-handover 'reality checks' stage. This role requires comprehensive experience of the specific measures installed (trained by experts or technicians) and the flexibility to provide on-site design solutions avoiding installation failures (e.g. MEV systems controls placed at a non-reachable height). Robust project planning and management in such complex refurbishments would also ensure a project's stability, securing best practice performance in construction beyond market turbulences.

Current building design standards and high low-carbon specifications are become a priority for design teams. Design solutions that involve high performance modelling assumptions of measures and systems may tick all boxes of energy standards however, the factors affecting building underperformance and user satisfaction lay on basic architectural design and installation principles that are often placed in second order. New challenges on design may involve high level dynamic modelling tools that incorporate technological innovation in buildings' refurbishment; however more critical approaches on the design stage from the design teams are required keeping in balance technical specifications and user-centre solutions.

Finally, as discussed above, low-carbon combined systems require multiple skills and expertise on combined low-carbon technologies. Certification of skills on new technologies is often undermined by online courses on individual systems lacking a 'whole-house' approach and practical experience to combined systems. In the building industry, low-carbon multi-skills/knowledge on combined systems need to be supported by practice-based training on actual low-carbon deep refurbishment trials similar to the RfF competition in the UK. This would allow for the creation of low-carbon training hubs in which theory is put into practice.

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