Proceedings of Conference: ***Adapting to Change: New Thinking on Comfort*** Cumberland Lodge, Windsor, UK, 9-11 April 2010. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Integrating an occupant-centred building performance evaluation approach to achieve whole-house and low-carbon retrofitting of UK homes

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ABSTRACT

This papers seeks to integrate an occupant-centred building performance evaluation approach into management and design interventions for achieving ambitious, large-scale, whole-house and rapid retrofitting of existing UK housing. A portfolio of building performance evaluation techniques, encompassing energy auditing, physical in-use monitoring of the internal thermal environment, and occupant feedback surveys, are identified which can be deployed *before* and *after* retrofitting existing housing. The various techniques are categorised as short-term feedback (snapshot) or long-term evaluation depending upon their duration. A number of these techniques are empirically-tested, either as a one-off or over a few months, 'before' refurbishing two different case study house types of different age groups, as part of the ongoing Technology Strategy Board's *Retrofit for the future* programme. The empirical application shows, how findings from various occupant feedback techniques are triangulated against the physical monitoring and measurement of the performance of the dwellings, and influence the selection of suitable user-centred low-carbon retrofitting design interventions. It is hoped that findings from this paper will inform and advance the debate of undertaking user-centred low-carbon retrofitting rapidly on a large-scale.

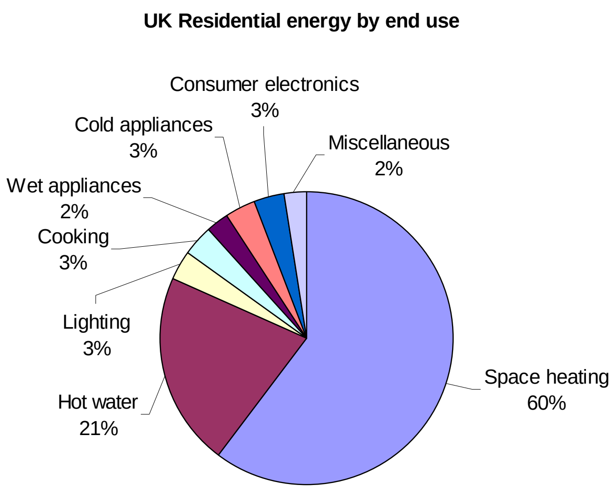
KEY WORDS

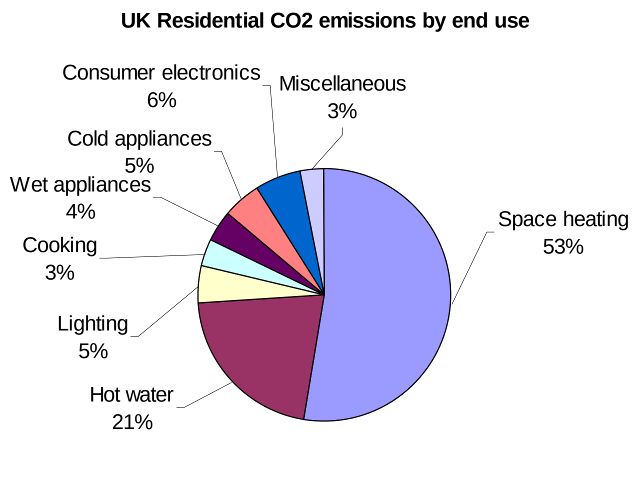
Housing energy performance, occupant feedback, post-occupancy evaluation, low carbon retrofitting

1. Introduction and background

Buildings, and especially the housing sector would need to deliver significant reductions as part of the UK Government's climate change targets, given that energy use in UK's 26.1 million residential dwellings generates about 27% of nation's CO_2 emissions (DEFRA, 2006). The Climate Change Act of 2008 legally commits the UK government to reducing CO_2 emissions by 80% by 2050 over 1990 levels (DECC, 2009a; 2009b). The Act's interim target of reducing emissions by 26% by 2020 has been subsequently tightened to 34% by statute (OPSI, 2008). As a guideline, household energy consumption is in the range 21-22,000 kWh a year, for all energy use in the home, from all sources of fuel (Boardman, 2007b). The proportions of energy use from various activities in housing are shown in Figure 1, which illustrates that the major portion of energy consumption is in space heating (60%) which is associated with 53% of CO_2 emissions, followed by hot water (21%). At the same time, energy demand has grown fastest from appliances over the last ten years, and in CO_2 terms, lights and appliances are more important, because electricity is more polluting than gas (CLG, 2006).

Figure 1. Breakdown of domestic energy use and CO2 emissions by end use
(Source: DEFRA, 2007; SDC, 2006)





If a significant reduction in existing domestic energy consumption is to occur in the UK to meet the national climate change targets, given that at least 75 per cent of the homes that will be standing in 2050 have already been built, it will be necessary to undertake extensive refurbishment (retrofitting) of the current housing stock to improve the fabric as well as the energy-consuming services within domestic properties (Beddington, 2008; Gupta, 2009). The challenge is set to increase, as the number of households will rise due to increasing population and falling household size (DECC, 2009b). Also recent studies indicate that the deployment rate of many of the interventions needed, and the effectiveness of them in practice, will make it extremely challenging for the UK to meet its 2020/2050 CO_2 reduction targets (Crosbie and Baker, 2009; Summerfield et al., 2009).

1.1 Programmes for large-scale, whole-house low-carbon retrofitting of UK homes

To address these concerns, in February 2009, the Government announced the 'Great British Refurb' programme and published its Heat and Energy Saving Strategy (HESS) consultation that details a radical shift in its ambitions to improve the energy efficiency of homes, by setting out an aim for emissions from existing homes (and non-domestic buildings) to be approaching zero by 2050 (DECC, 2009b). A 'whole-house' low-carbon retrofitting approach was introduced, which considers a household's energy needs and CO_2 impacts as a whole, and establishes a comprehensive package of measures to address them, which also includes renewable energy measures where appropriate to the property (HM Government, 2009). A key benefit of the 'whole house' approach is that it ensures that the needs of the property are assessed as a whole, that they happen in the right order, and that disruption is minimised (DECC, 2009b; HM Government, 2009). As part of HESS, the Government plans to provide the capacity to deliver comprehensive, whole-house solutions to 400,000 homes a year by 2015, extending to approximately 7 million homes across the UK by 2020, and to make cost-effective, energy efficiency measures available to all households by 2030 (DECC, 2009b). To deliver these targets, a community-based co-ordinated approach called Community Energy Savings Programme (CESP) is to be deployed post-2012, working door-to-door and street-to-street to cover the needs of the whole-house (DECC, 2009a). The whole house approach is also recommended by the Committee on Climate Change and supported in the UK Low Carbon Transition Plan (HM Government, 2009).

Within this context, a number of UK Government and Semi-government departments have launched competitions with generous funding to address this substantial challenge of volume, whole-house, rapid and low-carbon refurbishment of both public and private housing. These include the Technology Strategy Board's (TSB's) *Retrofit for the future programme*[1], Energy Technology Institute's (ETI's) *Buildings Call*[2] and the Department of Energy and Climate Change's *Low carbon communities call*[3].

However it is now increasingly recognised that technological solutions to domestic energy reduction are insufficient, and cannot guarantee energy savings without the cooperation of occupants (Bordass and Leaman, 2005a; Crosbie and Baker, 2009).. Given that identical homes, with different occupants, can vary in energy use by a factor of two to three (Steemers and Yun, 2009), yet the evaluation of user perceptions and behaviour in relation to building performance in housing is an emerging area.

Although the aforementioned funding programmes have emphasised that it is vital to understand the effectiveness of energy-efficiency interventions from the occupants' perspective, the focus of occupant feedback has been either on new-build or post-refurbishment (Energy Saving Trust, 2009a; Energy Saving Trust, 2009b; Gupta and Chandiwala, 2009a). So far, no critical analysis has been undertaken by applying occupant feedback techniques *before* improving existing housing i.e. *pre-refurbishment*, especially in the context of volume refurbishment. To improve the

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[1] http://www.innovateuk.org/ourstrategy/innovationplatforms/lowimpactbuilding/lowimpactbuildingcompetitions.ashx
[2] http://www.energytechnologies.co.uk/Home/Technology-Programmes/Buildings/Optimising_Thermal_Efficiency_Project.aspx
[3] http://www.decc.gov.uk/en/content/cms/news/pn109/pn109.aspx

uptake and effectiveness of household energy efficiency and low-carbon interventions, it is essential and inevitable to address this current gap in knowledge. This paper therefore, seeks to address the question of how to integrate occupant-centred building performance evaluation (comprising physical in-use monitoring, energy assessment and occupant feedback) into management and design interventions for achieving ambitious, large-scale, whole-house and rapid retrofitting of existing housing.

2. Occupant-centred building performance evaluation approach for low-carbon retrofitting of UK homes: Need and constituents

Traditionally the evaluation of housing performance has consisted of either physical monitoring or user satisfaction surveys, but these two are rarely related to each other as they cut across different disciplines of building science and social science (Stevenson, 2009). Also, this evaluation is usually done post-refurbishment. The evaluation hence, does not take into account any baseline information about the existing house, including its energy performance. It also misses the opportunity to maximise the benefits that can be easily achieved from a whole-house retrofit by addressing occupant concerns of space or other issues that might not traditionally form a part of retrofit geared towards reducing energy use, but can substantially add to the perception of comfort for the occupant.

Therefore to get a complete picture of the actual performance of a dwelling both from a technical and occupants' perspective, the 'soft' data collected from occupant feedback techniques, need to be correlated and triangulated against the quantitative data collected by measurement and monitoring of the physical performance of a dwelling. A third parameter involving simplified building modelling of the dwelling's energy use such as a SAP assessment can further help in identifying issues with current refurbishment methodologies by highlighting discrepancies between actual and modelled data and provide an in-depth and cohesive evaluation of energy use factors within the dwelling. Such an approach has also been termed as *building performance evaluation* (BPE), and helps to verify how a dwelling is actually being used, what the delivered energy use and carbon emissions are in reality, and how occupants perceive comfort and satisfaction, and what their expectations are. Pre-refurbishments, such findings also help in selecting appropriate user-centred interventions for improving the performance of the dwelling.

Even findings from the recently-completed EPSRC/Carbon Trust funded CaRB project have confirmed that valuable new insights can be gained by collecting hard data, i.e. measurement, monitoring, questionnaires and surveys, in existing buildings (Lomas, 2009). In fact there is ample scope for learning in the average home, where there is huge variability in terms of the acquisition, default setting and day-to-day use of heating systems and appliances, and where occupant 'behaviour' is central to consumption levels (Lutzenhiser, 1993). Such an evaluation of user perceptions and behaviour, has rarely been extended into the *pre-refurbishment* stage, whereby occupants' perception of comfort, satisfaction, behaviour and expectations could be combined with assessment of existing energy consumption and physical in-use monitoring to inform both briefing and solutions for low-carbon domestic refurbishments.

In fact valuable benefits occur in undertaking building performance evaluation during the pre-refurbishment stage, for the design team, clients as well as occupants. Starting at the *pre-refurbishment* stage helps the design team to establish and calibrate some of the briefing requirements (of achieving whole-house low-carbon), by using POE techniques to understand and learn from, the actual performance of the house to be refurbished against achieved realities, both from a technical and occupant's perspectives. Such an evaluation also allows the client (which could be a local authority, RSL or a developer in the housing sector) to require the design and building team not just to commit to POE of the outcome, but to operate a management system that is performance-driven, constantly reviewing likely outcomes against client and design aspirations, managing expectations and making the maximum use of feedback throughout the procurement process. For occupants (residents), a pre-refurbishment occupant feedback approach, empowers them to become part of the low-carbon interventions which minimises their unintended consequences. Wastage of energy is reduced which improves the quality and effectiveness of the low-carbon interventions. All this improves occupants' perceived value of low-carbon housing refurbishment.

2.1. BPE: triangulating physical performance against occupant feedback

While a universal, standard protocol for BPE has its attractions, several recent studies confirm that one size will not fit all. A balanced approach to suit the specific needs of the project and the client makes more sense, even during pre- and post-refurbishment stages of housing. Usually a *multi-modal* method is used for gathering information about the case study dwelling(s), involving desktop research to establish basic background information, preparing technical data pro-forma to establish construction as well as predicted and actual building performance, data-logging temperature and humidity, alongside questionnaire surveys and semi-structured interviews with key actors to gauge occupant satisfaction and thermal comfort.

Typically, an occupant-feedback based BPE approach includes:

- *Fabric testing* (to assess the thermal performance of the fabric especially heat losses);
- *Energy assessment and survey* (Energy assessment based on SAP modelling, annual and monthly delivered energy use from meters, break down of energy use by end uses especially appliances and hot water);
- *In-use monitoring* (of internal and external temperature, humidity, lighting, CO_2 levels, water consumption, opening/closing of doors and windows using data loggers, wireless sensors and/or whole-house monitoring kit); and
- *Occupant feedback* (on behaviour, perceptions, comfort and satisfaction levels using questionnaire surveys, interviews and activity log sheets). However, not many examples of this approach are available at a pre-refurbishment stage, as feedback and monitoring for evaluating housing performance has itself been very limited.

Based on an extensive review of literature and also drawing from published research on application of BPE (Andreu and Oreszczyn, 2004; Energy Saving Trust, 2009a; Gupta and Chandiwala, 2009b; Macintosh and Steemers, 2005; Stevenson and Rijal, 2008), Figure 2 summarises the various techniques that can be used for each aspect of BPE mentioned before, and compares which of these are applicable at the pre-and post- refurbishment stage. Techniques used for TSB case studies for pre-retrofit building performance evaluation are discussed in detail in the next section.

Figure 2. Techniques of measurement, monitoring and occupant feedback during pre- and post- refurbishment of dwellings

Building performance evaluation	**Technique**	**Pre-refurbishment**	**Post-refurbishment**
Fabric testing	Infrared thermography (external façade, openings, corners, junctions)		
	Co-heating test		
	Air-pressure testing (air permeability rate and pathways of air leakage)		
	Photographic survey		
Energy assessment and benchmarking	Energy modelling (SAP)- establish baseline energy use and model refurbishment strategies		
	Detailed energy survey - CIBSE TM22 Energy Assessment approach, degree day analysis, control charts, Benchmarking energy use and CO_2 emissions		
In-use measurement and monitoring of the physical environment	Thermal environment – external and internal temperature, humidity		
	CO_2 levels (internal air quality)		
	Daylight factor measurements using lux meter		
	Window opening measurements		
	Appliances audit		
	MVHR system- electricity use of pump and air flow rate		
	Performance of low/zero carbon technologies - heat pump, micro-CHP, solar PV, solar thermal, micro-wind		
	Whole house kit - Delivered energy (gas, electricity), appliance energy using plug-in meters, domestic hot water using heat meter, Water consumption		
Occupant feedback survey	Questionnaire surveys		
	Open-ended semi-structured interviews - occupants		
	Open-ended semi-structured interviews – design and build team		
	Heating schedule diary		
	Thermal comfort diary		
	Appliance energy usage questionnaire		
	Field observations of user behaviour		
	Occupants' video diaries		
	Focus groups		

For example, there is not much point in undertaking an expensive co-heating prior to refurbishment, although an air-permeability test can be scheduled at both pre- and post-refurbishment stages. In fact, such a test will show pathways of air leakage during pre-refurbishment, which can be addressed during refurbishment. On the other hand, most of the occupant feedback techniques can be used at both pre- and post-refurbishment stages, and the findings they reveal can be can be inter-related and compared, to ascertain if the low-carbon interventions have really had a tangible effect on energy use, CO2 emissions, and occupant comfort and satisfaction. However the focus of this paper is on the pre-refurbishment phase, which is why specific techniques for evaluating the performance of a house during pre-refurbishment are explained in the following section focussing on the TSB retrofit case study projects.

3. Case study dwellings

The two case studies presented in this paper are drawn from the TSB's Retrofit for the future (RfF) programme, particularly Phase 1. The TSB's RfF programme aims to deliver a minimum of 100 exemplar demonstrator houses in the social housing sector that target minimum cuts of 80% in energy consumption compared to existing use, followed by extensive post-refurbishment monitoring of physical performance, as there is a lack of feedback available on the real operation and actual performance of homes. Since both case studies are social housing, in this regard, it is important to understand the difference between user satisfaction with the home and tenant satisfaction with landlord services. In each of these case studies, clients are also more interested in understanding and improving building performance, occupant satisfaction and productivity, while leading design and building teams are beginning to realise its importance to their future credibility.
The two case study projects have been awarded funding under Phase 2 of the TSB RfF programme to implement the selected low-carbon interventions in latter part of 2010. In the future, this will allow an evaluative comparison of the performance of the refurbished homes from a technical and occupants' perspective, to pre-retrofit monitoring and occupant feedback. In this paper, the focus is on occupant feedback and physical monitoring during the pre-refurbishment stage.

3.1 Background to the case study projects; Rosyth and Oxford

The first case study house is a two-bed, end-terrace property (area=77.4m^2) located in Rosyth, Scotland. The housing has no-fines concrete cast in situ walls, with a concrete ground floor slab, internal brick/block walls and a timber trussed roof. The house has a north-south solar orientation. The original development was built in the early 1970s to house service personnel from the Rosyth Naval Base. Improvements in the last few years, in line with the Scottish Housing Quality Standards, have resulted in properties that meet modern living standards within a sustainable and thriving community.

Figure 3 Front and rear views of Rosyth case study dwelling

The second case study house is a typical 19th century, solid brick walled, slate roofed, two-bedroom end terrace house which has had some refurbishment in recent years (area=76.9m^2). There have been two extensions made to the property, which have unfilled cavity walls, concrete ground floor and a flat roof. The house front has a south-west solar orientation. The building is located close to central Oxford and whilst it is not in the central conservation area, there is a strong Victorian vernacular which is of historic value. The outward appearance of the properties is hence, controlled by planning and local societies and interest groups through the consultation process.

Figure 4 Front and rear views of Oxford case study dwelling

Both the houses are currently occupied by two people (couple) each, and also have continuous occupancy, with one occupant in each dwelling staying in the house most of the weekends and weekdays.

3.2 Fabric testing

Preliminary thermal imaging and photographic survey was carried out to detect key problems such as areas of damp and mould, boiler insulation levels, blocked radiators and any external factors (solar access for PV) which might influence strategies.

In Rosyth, the air pressure test showed a result of 9.97 $m^3/h.m^2$ at 50 Pascals. The house was generally in good condition with no signs of water ingress or mould. The test showed that some remedial sealing could bring this figure even lower. Air leakage was largely noticed around window casements, through gaps around the loft hatch and gaps left around service pipes to radiators and the boiler. In Oxford, the air pressure test result of 7.55 $m^3/h.m^2$ at 50 Pascals, was found to be substantially lower than the 10 $m^3/h.m^2$ at 50 Pascals required by the current building regulations. This reflects the good workmanship in Victorian dwellings.

3.3 Energy assessment and monitoring

Fuel bills for one year for both gas and electricity were analysed to understand energy use in the dwellings. For both the houses, the billing period was based on actual readings and not estimated bills. A SAP 2005 analysis was also carried out to further assess the difference in actual and modelled results. Since most retrofits only involve an RDSAP analysis to understand and predict the energy use and recommend strategies, this comparison allowed to understand the discrepancy in following only one approach.

As per SAP 2005 assessment of the *Rosyth* dwelling, the total electricity requirement (including lighting and fans/pumps) was estimated to be around 905kWh. However, one year analysis of the electricity bills which also included the appliance load showed 4364kWh of electricity units used. The house had a very high appliance load with multiple television sets and other ICT equipment which was evident in the site visit. Even though SAP does not account for appliances, the electrical use is more than four times of what is predicted. It is also noteworthy, that increase in appliances and equipments in dwellings is a major cause of rising energy use in spite of efficiency gains through technological improvements and any retrofit of existing housing should consider how this use can be measured and accounted for. The actual annual gas use is about 16,096kWh which is less than what is predicted by SAP, 22,835kWh. The actual total energy use per unit area for the house is about 264kWh/m^2/yr (Predicted 307kWh/m^2/yr).

Figure 5 Energy assessment- Rosyth: SAP model and fuel bills

Rosyth - SAP model	Total consumption (kWh)	Cost (£)	Per unit area (kWh/m2)
Gas	22,834.52	372.21	295.1
Electricity (Lighting +fans/ pumps)	904.85	98.43	11.69
Total energy	**23,739.37**	**470.64**	**306.79**

Rosyth - Bills	Total consumption (kWh)	Cost (£)	Per unit area (kWh/m2)
Gas (Sep 08- Oct 09)	16,096.16	709.74	208
Electricity (Lighting + fans/ pumps + appliances) (18June 08-21 June 09)	4364	604.9	56.4
Total (energy only)	**20,460**	**1314.64**	**264.4**

For the *Oxford* house, SAP 2005 estimated the total gas requirement to be about 24,800kWh, while the annual gas use from fuel bills was found to be only 9465kWh. This discrepancy in modelled and actual energy use was further explained by monitoring of internal temperatures (explained in a later section), which showed that average temperature in rooms was maintained at 14-18°C and hence, the annual gas bills for were less than half of what SAP predicted. The occupants also complained about a 'cold' house which was difficult to heat due to lack of insulation and rising fuel costs. The total electricity requirement (including lighting and fans/pumps) was estimated by SAP to be around 803kWh. The fuel bills which additionally included the appliance load showed 2481kWh of electrical units used. The actual total energy use per unit area for the house is about 155kWh/m2/yr, less than half of the predicted use at 333kWh/m2/yr.

Figure 6 Energy assessment- Oxford: SAP model and fuel bills

Oxford - SAP model	Total consumption (kWh)	Cost (£)	Per unit area (kWh/m2)
Gas	24,797.14	404.19	322.42
Electricity (Lighting +fans/ pumps)	802.52	57.14	10.44
Total energy	**25,599.66**	**461.33**	**332.86**

Oxford - Bills	Total consumption (kWh)	Cost (£)	Per unit area (kWh/m2)
Gas (29 Jan 08-28 Jan 09)	9465.16	336.05	123.08
Electricity (Lighting + fans/ pumps + appliances)	2481.00	354.15	32.26
Total (energy only)	**11,946.14**	**690.2**	**155.35**

3..4 In-use Monitoring and measurement of Physical data

Quantifiable 'hard' data was gathered for a number of parameters within the house and included long term monitoring of temperature, humidity and lighting (living room) over a period of two months as well as spot readings of air quality (CO_2 levels) and light level (lux) readings to deduce the daylight factor for internal spaces.

3.4.1 Temperature monitoring

Temperature was monitored in 3 internal spaces (living room, master bedroom and second rear bedroom) and another logger measured external air temperature. The table below shows the average temperature monitored over the duration.

Figure 7 Average monitored temperatures

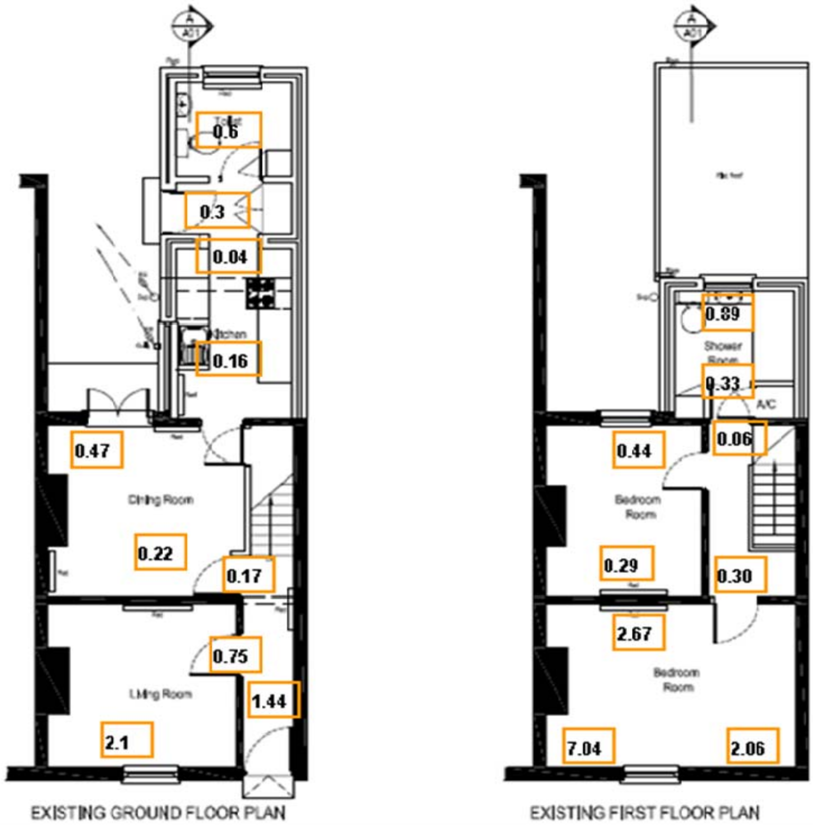
Rosyth Average temperatures (Degree Celsius)				
	External	Living room	Master bedroom	Rear bedroom
October	11.1	20.8	19.6	20.3
November	6.8	18.8	20.4	19.4
December (1-15)	4.1	19.0	20.6	19.1
Oxford Average temperatures (Degree Celsius)				
	External	Living room	Master bedroom	Rear bedroom
October	11.0	18.4	16.8	17.9
November	8.05	17.05	14.35	16.20

Rosyth, has a constant temperature of about 19-20°C, inspite of the variation in external temeprature. On the other hand, Oxford house has much lower temperature range of about 14-18°C. The temperatures in November are lower by 1-2°C in the same space as compared to October. The heating schedule also shows a marked difference for the two months. This shows that the users are aware about the difference in the external temperature and/or the cost of fuel and use their heating system in accordance with the weather. While in October, the heating was only switched on in the morning and the evenings, in November, the heating is almost continously on but still unable to reach comfort temperatures.

3.4.2 Natural light - Daylight factors

Monitoring showed good dalylight levels in most spaces within the Rosyth house. On the contrary, the Oxford house had very low levels of natural light with most internal spaces recording daylight factors of as low as 0.2-0.4%. The only exception were the main bedroom and the sitting room at the front of the house which had daylight factors of more than 2%. This confirmed the concerns raed by the residents in the interview and occupant satsifaction questionniares.

Figure 8 Daylight factors in Oxford house



3.4.3 Indoor air quality

Air quality (CO_2 levels) were measured as spot readings at different places in the house, using a CO_2 sensor. The Rosyth house was regularly ventilated and had good indoor air quality. The Oxford house however, showed CO_2 levels of averaging at 1300ppm with the sitting room as high as 1395ppm.

3.4.4 Window opening measurements

In the Oxford house, a further parameter was studied in detail; windows were monitored to gauge how often the occupants ventilate the house as the air quality spot readings (CO_2 sensor) readings showed high levels of CO_2 in the air which exceeded the recommended guidelines and could have direct health consequences. Window loggers were placed on four windows in different parts of the house. All windows were selected based on the occupants' response of windows they most frequently used. Out of the four, one logger (living room) did not pick up any data. Figure 9 shows the monitoring results.

Figure 9 Oxford case study: Window monitoring results

Master bedroom		**Kitchen window**		**Bathroom window**	
Date	**Time (open)**	**Date**	**Time (open)**	**Date**	**Time (open)**
20/11/2009 09:44	Logger installed	20/11/2009 09:33	Logger installed	20/11/2009 09:48	Logger installed
21/11/2009 08:06	Open for 4hrs 37 min	22/11/2009 14:17	Open for 4 minutes	21/11/2009 14:00	Open for 22 minutes
22/11/2009 08:27	Open for 3 hours 33 minutes	23/11/2009 16:54	Open for 1hour 5 minutes	25/11/2009 06:16	Open for 2hrs 15 minutes
09/12/2009 06:20	Open for 10 minutes	23/11/2009 18:20	Open for 8 minutes	08/12/2009 17:11	Open for 1 hour 19 minutes
13/12/2009 08:43	Open for 3.5 hours	12/12/2009 18:35	Open for 14 minutes	12/12/2009 08:29	Open for 20 minutes
18/12/2009 09:22	Logger removed	23/11/2009 18:20	Open for 8 minutes	18/12/2009 09:18	Logger removed
		18/12/2009 09:14	Logger removed		

In a period of 28 days, the windows in each space have only been opened on an average on four days. The master bedroom window was opened for the longest duration while the kitchen and the bathroom windows were used for much lesser time. This shows that the occupants probably do not realize the consequences of poor air quality in the house. As evident by the temperature monitoring, the house has lower than average recommended temperatures. This might be another reason due to which the occupants prefer to not open the windows to reduce any further heat loss.

3.5 Occupant feedback survey

Occupant feedback survey is a combination of short term or one-off feedback techniques such as questionnaire surveys and semi-structured interviews as well as longer term techniques which require the occupants to record responses periodically (daily or more than once a day). The overall time period for collecting data is crucial with respect to understanding occupant behaviour and preferences while maintaining the occupant’s interest and engagement with the process. Hence, the time period should be carefully assigned for each of these techniques.

3.5.1 Occupant satisfaction questionnaire survey and Open-ended semi-structured interviews

An occupant satisfaction questionnaire was filled by each occupant individually to ascertain occupant satisfaction levels (noise, air quality, light, design and functionality of spaces) and occupant thermal comfort in the house at that specific moment. The questionnaire is a one-off feedback technique and carried out at the beginning of the study. It is accompanied by an open ended semi-structured interview which extends the range of criteria to include wider issues about the house, such as criteria on space and flexibility, best and worst aspects of the house as well as any future changes the occupants would like to be incorporated. These questions may provide important clues to understand how the house is used currently and how future needs can be efficiently incorporated within the retrofit.

Occupant survey highlighted key issues for Rosyth house. The heating system suffered from slow responsiveness and two radiators were not working at all. As a result, the house was generally very cold in the morning. The occupants also mentioned that they usually adjusted temperature directly from the radiators, even though, new timers were recently installed. The users also had positive feedback on the air quality and the day-light levels within the house, which was also evident in the physical monitoring. In terms of space and design, they found the house flexible and easy to use though preferred to have a bigger kitchen. The only other concern was related to noise from the exterior and the neighbour's house which could be heard inside due to lack of insulation in external and party wall and also due to the poor quality of double glazed windows.

The Oxford house occupant survey highlighted very different results as compared to the Rosyth house. While the users found that the heating system responded very quickly, it was unable to maintain the house at a comfortable temperature and the house generally felt quite cold. Again, the results from the physical monitoring confirmed this as average temperatures were 14-16 °C in some spaces. The living space was the only space where the secondary heating system helped to heat the room to a comfortable temperature. Occupants mentioned that they have adapted to this by putting on extra layers of clothing. The house also felt quite dark with the exception of main bedroom and sitting room/office towards the front of the house (facing south-west).

The users also mentioned a preference for a bigger living room to have space for a dining table by combining the living room and sitting/office space. Lack of sufficient storage space, and small rooms and kitchen was also frequently mentioned. Overall the occupants were generally very satisfied with the house due to the central location and the garden which formed a very strong focus of the house, despite all the issues previously mentioned. This showed that there was a high degree of 'forgiveness factor' which has been identified in the PROBE studies as well.

Occupants in both case study houses also mentioned their concerns about adapting the house for future use as each house had one occupant who continuously occupied the house due to health reasons.

3.5.2 Appliance energy usage questionnaire

Occupant feedback was also collected on appliance energy use. Though, outside the bounds of most refurbishment projects, increasing number of appliances in the house is driving up energy use within the domestic sector. The appliance audit consists of a list of appliances and equipment within each space in the house and the average daily usage hours. This provides an estimate about the electricity use, and the base load (always on devices) of the dwelling. The appliances energy use questionnaire can also highlight user preferences and can induce proenvironmental behaviour by generating awareness, such as switching off appliances from the plug socket. The Rosyth case study had a very high number of appliances and the questionnaire estimated an average use of about 7668kWh/year while for Oxford, it was estimated to be around 4829kWh/year.

3.5.3 Occupant completion of thermal comfort diary

The thermal comfort diary was based on five questions mainly on temperature and comfort preference vote and the level of activity and clothing on. Each question was linked to a scale of comfort, and the occupants recorded their response to the question three times a day, once in the morning, afternoon and late evening. The thermal comfort diary was to be filled by each occupant individually; on the days and time that they were present in the house. For the case studies, occupants recorded their thermal comfort data for approximately two months in the heating season.

Figure 10 Thermal comfort diary

Thermal Comfort Diary									
	12.10.2009			13.10.2009			14.10.2009		
Time:	9-12	12-18	18-21	9-12	12-18	18-21	9-12	12-18	18-21
How do you feel at this tim	11:30	16:46	20:20	10:35	15:50	21:00	9:25	17:25	21:00
Much too warm									
Too warm									
Comfortably warm		x	x	x	x	x			x
ortably neither warm nor cool	x						x	x	
Comfortably cool									
Too cool									
Much to cool									
You would prefer to be:									
Much cooler									
A bit cooler									
No change		x	x	x	x	x			x
A bit warmer	x						x	x	
Much warmer									
Rate of overall comfort									
Very comfortable				x		x			x
Moderately comfortable		x	x		x				
Slightly comfortable							x		
Slightly uncomfortable	x							x	
Moderately uncomfortable									
Very uncomfortable									
Activity in the last hour									
Sitting - passive						x	x		x
Sitting - activity	x		x					x	
Standing - Relaxed				x					
Walking - indoors		x			x				
Walking - Outdoors									
Clothing									
Number of layers	1	1	2	2	1	2	1	2	2

Rosyth

As shown in figure 11 and 12 for residents of the house in Rosyth, the morning time over the two months is split between either being comfortably warm or too cool. This corresponds with the occupants' response of cold mornings in the winters.

Figure 11 Rosyth: Temperature vote (occupant 1)

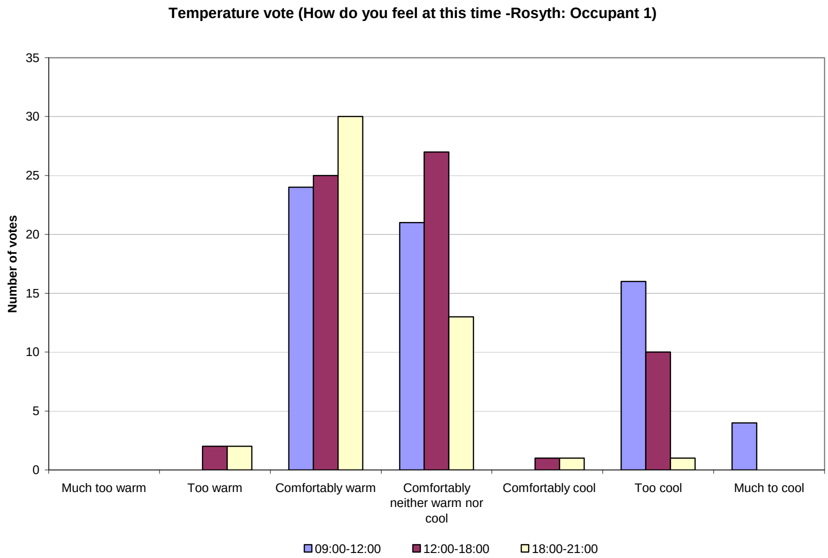
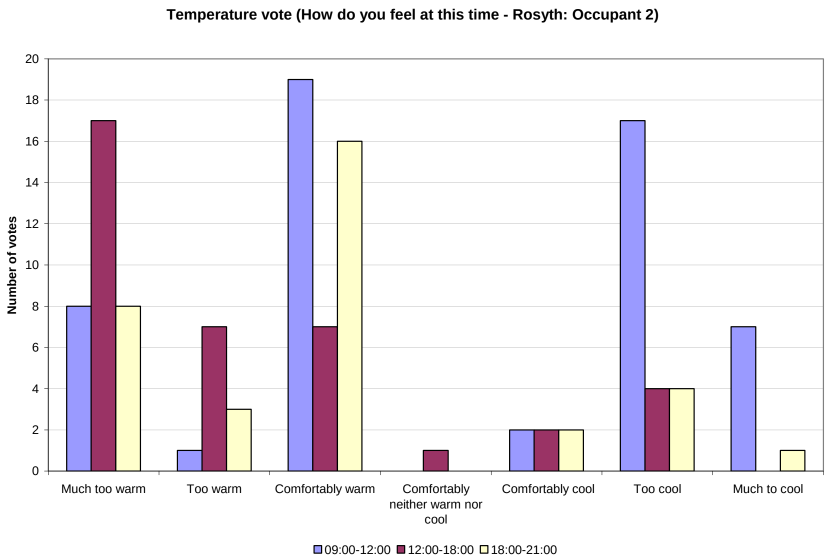


Figure 12 Rosyth: Temperature vote (occupant 2)



Also, the evening time over the entire duration is generally on the warmer side, showing that the house is probably continuously heated through the day, which ensures that evenings are much warmer. While the occupant, who continuously spends time in the house, has a consistently high response of comfortably warm and comfortable conditions throughout the day, the second occupant's response is more varied over the two months.

This is also evident when the results from other questions pertaining to the preferred temperature as well as overall comfort are compared between the two occupants. The first occupant, who stays indoors, has a very high rate of overall comfort and this is reflected in the preferred temperature to remain the same mostly. The second occupant, comparatively, has a lower rate of overall comfort, with majority of the votes in the ‘uncomfortable’ range.

Oxford

In the Oxford case study, (figure 13), both the occupants feel comfortably warm or comfortable, even though physical monitoring showed that the temperature in the house was much below the recommended standards. The occupants complained about the inability to heat the house to a desired level as well. The results from the thermal log should be assessed keeping in mind that the occupants have adapted to this cold house by wearing more clothes even when indoors. In spite of this, one of the occupants has rated the house to be cold especially during mid-day and the evenings, which corresponds with the preference for a warmer house (figure 15). However occupant 1, who continually inhabits the space has adapted to the house, and prefers no change (figure 14).

Figure 13 Oxford: Temperature vote (Occupant 1)

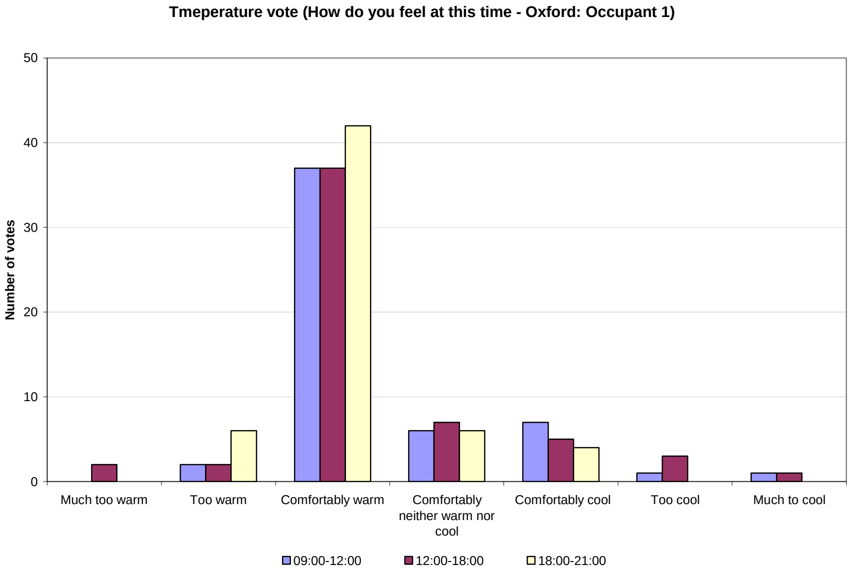


Figure 14 Oxford: Temperature preference vote (Occupant 1)

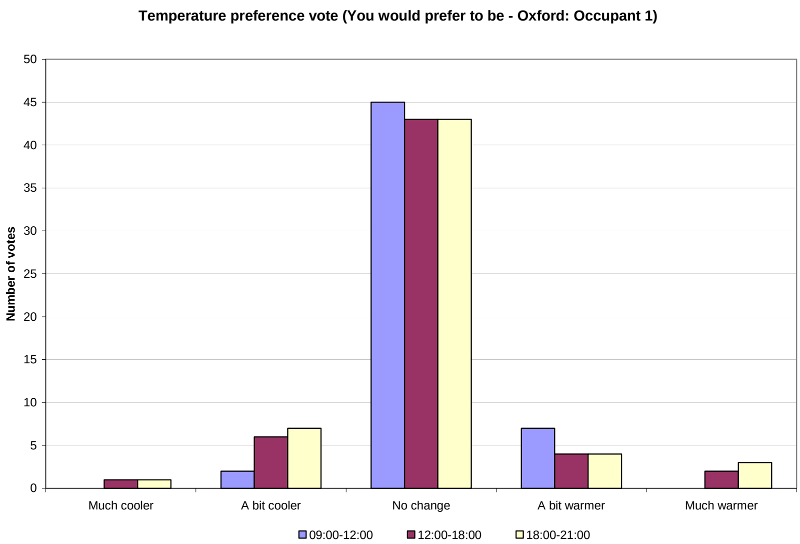
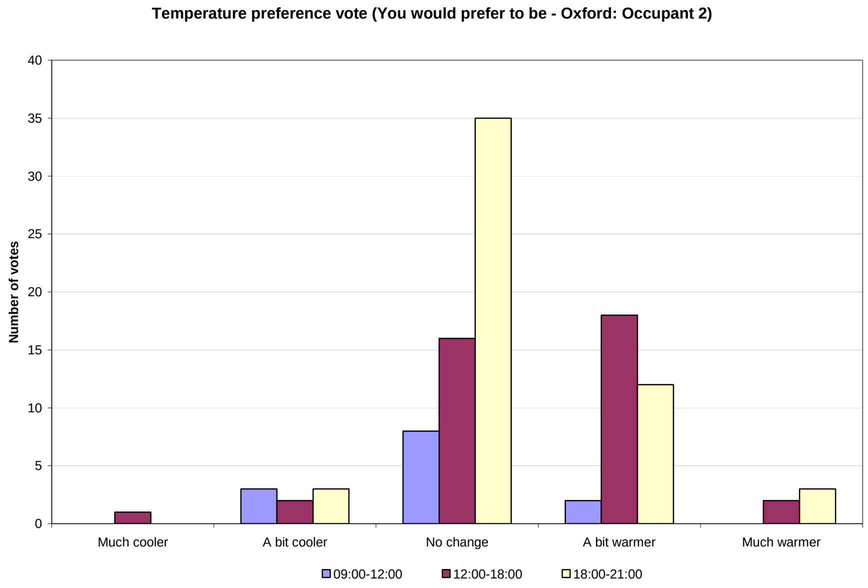


Figure 15 Oxford: Temperature preference vote (Occupant 2)



3.5.4 Heating schedule logging sheet

The heating system log sheet was designed to identify how the users operated the heating system and related controls as well as the number of hours typically in a day when the heating system was on. The logging sheet also recorded additional factors such as any open external door or window (which ameliorates the effect of heating), as well as supplementary heating within the space. Due to the time scale of this study, this is concentrated to two months of November and December, which provides a fair idea about the heating season.

The data for Rosyth is very erratic. The occupants mentioned in the interview that they only control the temperature directly from the radiators and do not use the recently fitted timer controls. Temperature monitoring revealed a constant 19-20°C in the house, which means the house, was almost continuously heated. This is similar to what the heating log shows, as at times, there are 3-4 start/stop times with no more than a 1-2 hour interval in the day when the heating system is switched off. Mainly, the heating system comes on between 7.00-9.00hours daily and is on till 23.00-24.00 hours.

The Oxford house has markedly different use in the months of November and December. In November, the heating is on usually from 4.30am to 6.30/7.00am and then again from 17.00-21.30hours. Occasionally, it is switched on in the afternoon as well from 12.00hours onwards till 21.30hours, probably on a particularly cold day. In December, the entries show the heating system is continuously on from 4.30hours in the morning to 21.30hours. Some days, the diary shows two start times in the day but only one stop time at night. It seems likely that the heating system is set to continuously on with a temperature setting and every time the user has manually increased the thermostat temperature in the day to kick-start the heating, another start time has been recorded.

The following section describes how these occupant feedback techniques along with physical monitoring, were applied to two case study dwellings to arrive at appropriate user-centred low-carbon solutions.

4. Influence of occupant feedback and physical monitoring on low-carbon refurbishment strategies

The physical monitoring combined with a range of occupant feedback and survey techniques provided robust information about the in-use characteristics of the house, how it is used, major problems with the current house and the users' expectations from the retrofit. Some key results and consequent interventions are summarised for each house.

Figure 16 Rosyth: Key results and Interventions

Rosyth: Key results	**Interventions**
• Un-insulated fabric • House cold in the morning required continuous heating to maintain comfortable temperatures • Ineffiecient heating system, slow to respond	Highly-insulated fabric, Triple-glazed passivhaus windows and, Efficient heating system
• The house was full of electrical appliances and equipment • Reflected in the unsually high electricity bills for a two bedroom house.	Provision of efficient A++ white goods, Automatic standby savers and voltage optimisation to minimise electricity wastage and Incorporation of 1kWp PV
• Lack of accoustic barrier from noise from external areas and the neighbour's house.	Insulate the party wall, high quality triple glazed passivhaus windows to reduce noise from the external environment as well as heat loss.

Figure 17 Oxford: Key results and Interventions

Oxford: Key results	**Interventions**
• Poor levels of daylight in most rooms, • Average daylight factors of less than 1, except the master bedroom and living room.	Roof lights incorporated in design with good low U-values to minimise heat loss
• Poor indoor air-quality in the house • Windows were monitored for 28 days and found to be opened on an average for only 4 days.	Incorporate mechanical ventilation in the house to maintain indoor air quality levels, Retrofit will lead to a well-sealed house further reducing natural air/ventilation pathways. The effectiveness of the MVHR system will be monitored technically (air flow and electricity use of the pump).
• Un-insulated fabric • Difficult to heat house to comfortable temperatures • Lower than average gas bills as the occupants are very careful with the use of heating system, given the rising costs of gas.	Highly-insulated fabric, Triple-glazed passivhaus windows and, Efficient heating system

5. Low carbon retrofitting approach influenced from BPE techniques

The individual interventions and requirements of the case study houses were combined to inform an overall low carbon retroffting approach.

Given the lack of insulation in the case study homes, and the concerns of the residents as the dwellings being cold, a 'low-energy first and then low-carbon' approach was adopted for these dwellings, by encouraging energy demand-reduction measures first, and then deploying a nominal level of well-proven zero-carbon technologies that can be easily integrated into the urban fabric. The overall objective was to arrive at a practical whole-house solution which can be rapidly replicated on a large-scale in the UK social housing stock to meet reductions above 80% over existing emissions. This is achieved by deploying an energy-efficient and air-tight building fabric with stringent U-values and minimal thermal bridging, leading to about a 65% reduction in energy use and emissions over the baseline. The demand for space heating, hot water and electricity is met efficiently by using a highly-efficient condensing boiler, A++ rated appliances and LED lighting, giving 75% reduction. Finally, on-site zero-carbon technologies, such as 3m2 solar thermal (hot water) and 1kWp solar photovoltaic (PV) systems are added to further reduce electricity and gas use and achieve an 85% reduction in CO2 emissions over the existing house. This exceeds the TSB target requirements of 17kgCO2/m2/yr and a primary energy of 115kWh/m2/yr, using the SAP extension sheet v1.6, supplied by the TSB RfF programme. Figure 19 and 20 show the modelled absolute reduction achieved for both the case study houses.

In addition, a low-maintenance 'fit and forget' approach was enouraged, so that all selected interventions minimise maintenance call-outs for the landlord and access-related issues for the dwellings, crucial in the social housing sector. To improve health, comfort and well-being of occupants, extra measures were incorporated, such as use of FSC-certified timber, low-solvent paints to improve the indoor air quality, and water-efficient fixtures to conserve water.

Finally, for both case studies, in line with a user-centred approach, a bespoke whole-house monitoring and feedback system is proposed to be installed to display real-time gas and electricity use, internal temperature, humidity, CO_2 levels, and any energy being wasted through open windows, unused equipment and lighting. This will help to empower occupants to monitor and control their energy use and associated costs.

Figure 18 Rosyth: Reduction achieved in CO_2 emissions and primary energy

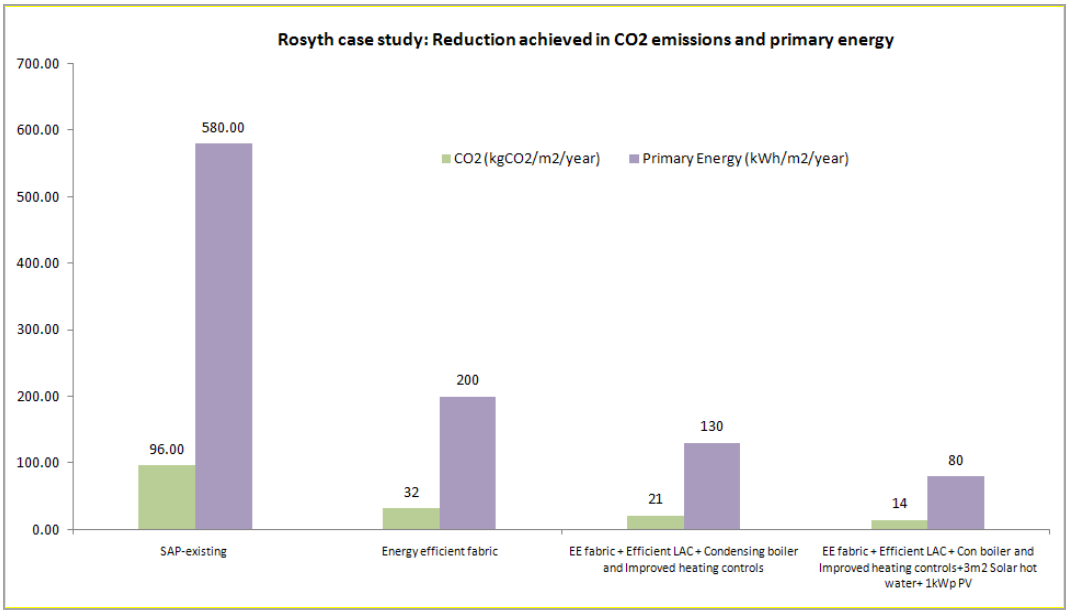
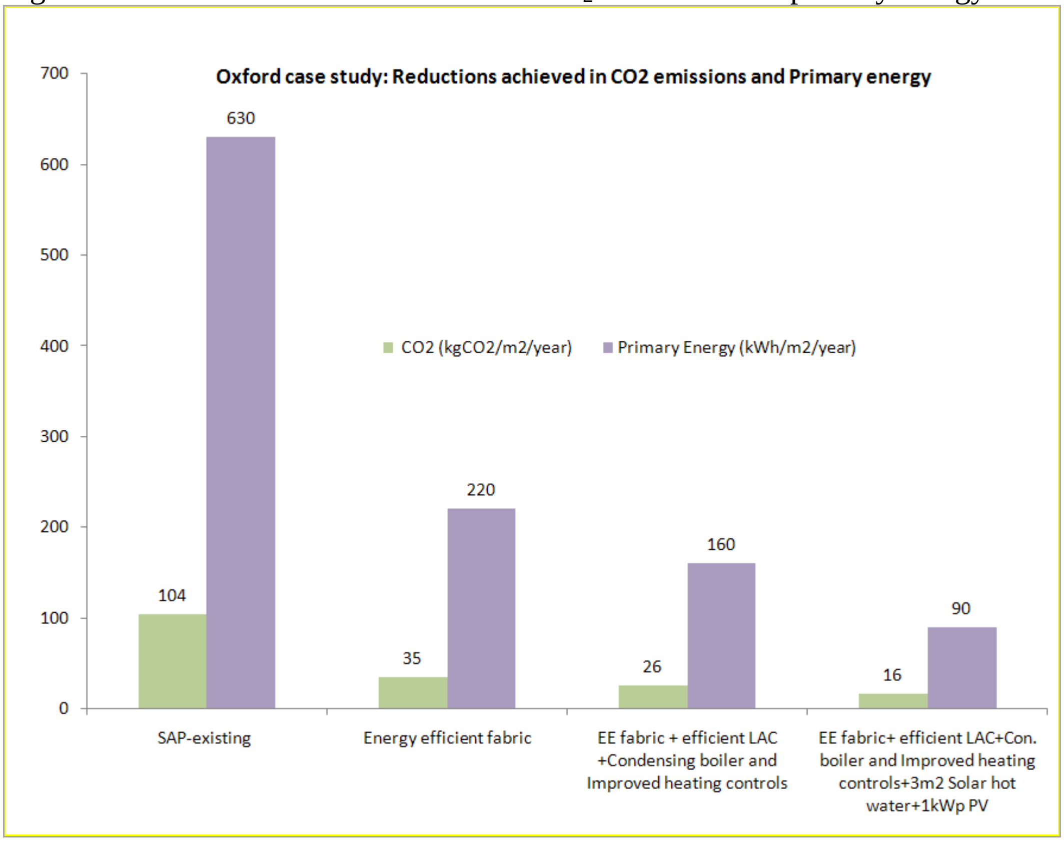


Figure 19 Oxford: Reduction achieved in CO_2 emissions and primary energy



6. Conclusions

This paper has demonstrated the need, importance and application of a range of occupant feedback techniques for low-carbon refurbishment of UK dwellings to achieve deep cuts in CO_2 emissions. The empirical application shows, how findings from various occupant feedback techniques are triangulated against the physical performance of the dwellings, and influence the selection of suitable user-centred low-carbon retrofitting design interventions.

The authors' experience with the aforementioned case study projects has revealed key lessons and challenges for the future, especially, focussing on 'need to know' rather than 'nice to know' factors, as there is relatively less time available to undertake comprehensive *pre-refurbishment* monitoring and occupant feedback surveys. Like new-build and post-refurbished dwellings, there are also particular issues related to privacy of residents, maintaining the interest of occupants to complete log sheets and thermal comfort diaries, and accounting for the increasing use of appliances by residents. These will need to be overcome if a standardised methodology is to be developed for this sector.

Also, integrating this methodology within a *Soft landings* (currently managed by BSRIA and developed in research led by Cambridge University) framework that outlines how a feedback process can be inbuilt into the brief using POE techniques (Bordass and Leaman, 2005b) would be highly desirable to establish and standardize protocols for large scale so that the results from such studies could be compared both pre- and post-refurbishment. Without such an evidence base, the ongoing effort for a rapid, low-carbon and large-scale refurbishment of UK homes, may prove to be ineffective or counter-productive.

Further field studies during pre-refurbishment of UK homes should be encouraged in different climates and cultures, which combine both occupant feedback and physical monitoring. There is a compelling need to apply such an approach to the owner-occupied homes, which forms about 75% of the UK housing stock. Particularly, seasonal effects that were not included in this study (due to time constraints imposed by the Phase 1 of the TSB Retrofit for the future programme) should be addressed in further research. Feedback to reveal the effects of other physical variables such as air movement and solar intensity, and non physical ones such as the perceived need for fresh air, as well as individual characteristics on occupant behaviour patterns and comfort is required, so that user-sensitive low-carbon interventions are deployed in improving the existing housing.

7. Acknowledgements

The authors gratefully acknowledge the residents of the case study dwellings in Oxford and Rosyth, for their co-operation during the study and for regularly completing questionnaire, diaries and heating log sheets. The authors are also grateful to Technology Strategy Board for providing funding for Phase 1 of the Retrofit for the Future programme. Thanks are also due to Home Group Housing and Oxford City Council, the owners of the two case study dwellings.

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