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Do deep low carbon retrofits actually work?

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Abstract

This paper presents the findings from building performance evaluation studies of two deep retrofits in UK – Victorian house and Modern 1990s house. Both case studies were designed to achieve 17 $kgCO_2/m^2/year$ (equivalent to 80 % reduction) and adopted a *fabric-first* approach. Post-retrofit, it was found that the Victorian house achieved a 75 % CO_2 reduction, while the modern house achieved 57 % CO_2 reduction over the baseline. Key reasons for these are higher than expected air-permeability rates of the building fabric post-retrofit, lack of occupant understanding in operating low carbon technologies and unusual electricity using behaviors of occupants particularly in the modern house.

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Keywords: Retrofit; energy performance; household energy; low carbon buildings

1. Introduction

The UK is legally committed to an 80 % greenhouse gas emissions reduction target for 2050 and to 5-year carbon budgets in the interim [1]. The 2011 UK Carbon Plan [1] states that "By 2050, all buildings will need to have an emissions footprint close to zero". Given that the UK's 26.1 million residential dwellings generate about 27 % of the nation's CO_2 emissions and 70 % of these will exist in 2050 [2], a key requisite to achieving these targets is to understand the potential and effectiveness of retrofitting the various dwelling typologies. Along with the UK's old housing stock, 13 million dwellings built before 1960 and 4.7 million built before 1919, all European countries are

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faced with the challenge of improving the energy efficiency of their large stock of inefficient housing [3]. To address this issue in the UK, the UK Government's Technology Strategy Board (TSB) sponsored the national Retrofit for the Future (RfF) programme from 2009-2013, to demonstrate innovative approaches to deep retrofitting of social housing stock, using a 'whole-house' approach for achieving an 80 % CO_2 emission reduction target.

This paper presents a systematic building performance evaluation (BPE) approach to assess the pre- and post-energy and environmental performance of two RfF dwellings, from technical and users' perspectives, from pre-retrofit through to design, construction, handover, and in-use stages. Both case studies were designed to achieve 80 % CO_2 reductions, i.e. 17 $kgCO_2/m^2$/year.

1.1. Retrofit for the Future programme

The Retrofit for the Future programme was a competition proposed to demonstrate whole-house approaches for achieving an 80 % CO_2 emission reduction target (for an 80m^2 semi-detached house, against a 1990 baseline (97 $kgCO_2/m^2$/yr)). 194 projects were awarded funding of up to £20 000 to develop a strategy towards meeting the target (Phase 1) and about 86 projects across the UK were awarded up to £150 000 to demonstrate the effectiveness of their strategy in real homes (Phase 2) [4]. In order to set a single target across the programme independent of location, building type and condition, an estimated average emissions figure for the UK housing stock was used. Whole house CO_2 and primary energy targets were calculated and expressed as 17 kg/m^2/yr and 115 kWh/m^2/yr respectively. The programme was a 'living lab' of many different experiments, and involved rigorous and systematic evaluation of each project, comprising short-term physical tests of building fabric; long-term physical monitoring of energy use and environmental conditions; standardized post-occupancy evaluation (POE) of primary resident experiences; post-construction reviews (PCRs) of construction quality and holistic review of projects [5].

1.2. Methodology

Methodologically, the requirement for Phase 2 was to take a 'whole house approach' to meet the target and to include a comprehensive post-retrofit monitoring strategy in accordance with provided specifications [3]. Also prescriptive were pre- and post-retrofit air permeability tests and thermography studies, and post-retrofit PCRs and occupancy surveys [4]. As-designed CO_2 targets were assessed using a modified version of the Standard Assessment Procedure (SAP) unless the dwellings were targeting Passivhaus. In addition to this, the particular methodology developed for the evaluations of the two dwellings in this study included pre-retrofit POE. Pre-retrofit evaluation was used to ascertain in-use characteristics and identify appropriate interventions for retrofitting. The evaluation also helped establish baseline performance and a reference point to which occupant behaviour and patterns could be compared. All proposed retrofitting improvements were therefore underpinned by this analysis of the occupant feedback and the physical monitoring survey, leading to a 'user-centred retrofitting approach' which intended to minimise rebound effects and unintended consequences [6].

Both projects followed a 'fabric-first' or 'low-energy first and then low-carbon' approach, by encouraging energy demand-reduction measures (fabric) first, and then deploying a nominal level of well-proven zero-carbon technologies that can be easily integrated into the urban fabric. Following the retrofit, a 2-year BPE study was conducted which included continuous remote monitoring of environmental parameters (indoor and outdoor temperature, relative humidity, CO_2 levels) in key spaces, smart metering of energy consumption cross-related with regular feedback gathered from occupants through questionnaires, interviews, walkthroughs and activity log sheets.

1.3. Two case study dwellings

Two case study dwellings, a Victorian and modern dwelling are the subject of the present study. Table 1 provides details of these dwellings. Due to cost concerns and the inability to sufficiently heat the solid-walled Victorian home, pre-retrofit temperature monitoring revealed that the house was constantly under-heated with the master bedroom generally maintaining a temperature between 14-16 °C and the living room just around 18 °C. In addition, daylight factors were poor (<1 %), indicating the need to open the dwelling up to more natural light. The pre-retrofit analysis findings reinforced the need to focus on highly efficient fabric to not only meet the programme target but to provide comfort to the occupants whilst balancing the need to bring in more natural light.

Table 1. House and retrofit details

An example of a column heading	Victorian	Modern
Year built	Pre-1919	1992
Built form	Solid wall end-terrace	Cavity-wall mid-terrace
Gross internal area (m^2)	78	84
Occupancy	2 adults	2-4 people (varies)

In the modern home, the almost full time, high occupancy density (four adults in an 84 m^2 home) meant that the electricity demand was significantly higher than that predicted by SAP. Given the high amount of electricity use and the associated CO_2 emissions, reduction of electricity use in the house was considered a key area for the retrofit stage. Such measures included an internal drying space for clothing and the installation of more efficient appliances. Though these measures do not have an effect on the SAP rating thereby not contributing to the 80 % modelled CO_2 reduction target, these measures do have a considerable effect on actual energy use and their associated CO_2 emissions. Aside from these additional considerations, the whole-house and fabric-first approach was still essential to meet the programme's target.

Both dwellings were retrofitted with front internal solid wall insulation (to preserve the original exterior façade), external solid wall insulation on the rear, cavity wall insulation where applicable, floor insulation and loft insulation. In addition, the Victorian dwelling had triple glazing installed. The heating and low/zero carbon technology strategy of both dwellings included condensing combi-boilers, and solar hot water and photovoltaic panels. The ventilation strategies were different. The Victorian dwelling incorporated a mechanical ventilation with heat recovery (MVHR) unit and the modern home depended on natural ventilation from in-built, secure, louvered, ventilation panels on the two levels and an automated roof-light. This strategy was selected since the occupants in the modern house were smokers and were accustomed to opening windows frequently. With regard to retrofit process, the occupants of the Victorian home were decanted and the modern home occupants were in-situ. Apart from minor annoyance brought up in occupant interviews for the modern home, no link at this stage can be made between process and overall outcome apart from theorizing that when construction teams are forced to work around occupants, work can be rushed and attention to detail can suffer. In the end, however, both dwelling's occupants found the retrofit process inconvenient.

2. Evaluating the impact of deep low carbon retrofits

2.1. Final energy assessment

Pre-1919 Victorian homes in the UK have an average mean energy use (heating and lighting) of 480 kWh/m^2/yr. Post-1990 dwellings' mean energy use is 270 kWh/m^2/yr. The difference is due to a progression in awareness and concern of fossil fuel consumption and a greater understanding of building physics as time passed [3]. Given this it was expected that the Victorian home would consume more energy and be more difficult to retrofit than the modern home. Interestingly, the Victorian home was consuming less pre-retrofit gas and electricity than the modern home (fig.1) and resulted in lower final consumption. The pre-retrofit analysis of the dwellings revealed that both houses had lower measured gas consumption (heating and hot water) as compared to predictions made by energy models, due to pre-bound effect [7].

Post-retrofit, it was found that the Victorian house achieved a 75 % CO_2 reduction while the modern house achieved only 57 % CO_2 reductions as compared to the retrofit programme baseline (table 2). Neither dwelling met the design target (80 % reduction). Interestingly however, the actual post-retrofit gas consumption figures for both houses were nearly identical to the design target figures (though slightly higher in the following year). Electricity use (determined by occupancy, behaviour, appliances etc.) in the modern house is almost three times the predicted due to unusual occupant behaviour which was identified through pre-retrofit evaluation. The following sections explore the reasons for the performance gap as assessed through building performance evaluations.

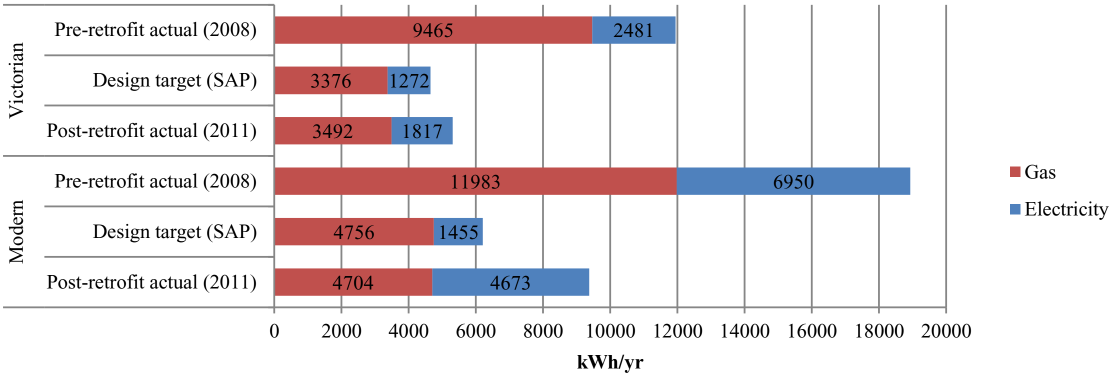

Fig. 1. Pre- and post- retrofit gas and electricity energy consumption figures

Table 2. Design and actual carbon performance of retrofits

An example of a column heading	Victorian	Modern
Pre-retrofit SAP ($kgCO_2/m^2/yr$)	104	62
Pre-retrofit actual ($kgCO_2/m^2/yr$)	40	70
Design target (SAP) ($kgCO_2/m^2/yr$)	17	17
Post-retrofit actual ($kgCO_2/m^2/yr$)	24 (two yr. mean)	42 (two yr. mean)

2.2. Fabric performance

The Victorian home was designed to operate with a whole house MVHR whereas the modern home was not. From the design stage, airtightness was an important part of the equation to meet fabric efficiency for the Victorian home. From the outset the target was clear and the construction team made an effort to seal the shell. Air tightness membranes were installed in first floor ceilings with all service pipe areas sealed. All gaps and holes in outside walls were filled. All junctions between floors and walls were sealed to ensure a low level of heat loss from air leakage. To achieve the required air tightness standards the contractor built in quality 'hold points' within the programme and care was taken to educate the personnel on site to ensure they understood the importance of the air tightness detailing and its impact on the performance of the building. Though the above effort was taken, the target was not achieved (table 3); furthermore, the Victorian home is among the 60 % of RfF dwellings with MVHR that did not meet an air permeability that would justify the need for the whole house ventilation system [8]. MVHR, where unnecessary, can be both a costly intervention (average cost of £6 117 in the RfF programme [9]) and can add a parasitic electricity load where they are typically in an always-on status. This trend of introducing MVHR systems in homes with inappropriate levels of air-tightness is happening in new-build housing projects as well [10].

Table 3. Air permeability results

An example of a column heading	Victorian	Modern
Pre-retrofit air permeability ($m^3/(h.m^2)$@50pa)	5.9	5.7 (mean of two)
Air permeability target ($m^3/(h.m^2)$@50pa)	1	3
Post-retrofit air permeability ($m^3/(h.m^2)$@50pa)	3.7 (mean of three)	6.5 (mean of two)
Air perm. rank among all 86 RfF projects	32	60

The modern home aimed to achieve the lowest air permeability allowed without requiring whole house ventilation (table 3); specifically the design team could not justify the additional cost and energy requirement of a whole house ventilation system against the small projected CO_2 emission reduction. Because low air permeability was not essential for the purpose of a ventilation system, it is possible less effort was put into communicating intent through to the construction phase, resulting in not only a missed target but higher air permeability than pre-retrofit.

Thermal imaging surveys were also performed pre- and post-retrofit to identify areas of building fabric heat loss. The areas with the most heat loss were found where connections had to be made between different materials, especially penetrations and where doors and windows interrupt the façade. Difficult connections proved to be at corners of the dwelling where walls meet the floor (especially ground) or roof. In the Victorian home notable heat loss was found where the front façade (internal insulation) met the corner of the end wall of end-terrace (external insulation). This demonstrates a potential outcome of working with protected facades. Much greater uniformity can be seen on the back of the property where external insulation was used throughout.

Post-retrofit U-value measurements were determined by placement of heat flux sensors on external walls and calculated with internal/external air temperatures adjacent to the sensor locations. In the Victorian dwelling, though the U-value on the north wall was higher (0.16 $W/(m^2K)$) than the as-designed U-value (0.135 $W/(m^2K)$) and on the south the U-value was lower (0.11 $W/(m^2K)$), the mean of the U-value measurements equals the as-designed projection. In the modern dwelling, the U-values (0.27 and 0.30 $W/(m^2K)$) were greater than the target U-value (0.15 $W/(m^2K)$). This can be a result of poor planning and communication resulting in improper installation of insulation and thermal bridging.

2.3. Environmental performance

Post-retrofit, the Victorian home exhibited steady and satisfactory temperature and relative humidity (RH) levels (according to design guidance) and a significant increase in occupant satisfaction with comfort conditions and internal light levels. Additional daylight, elimination of draughts and temperature control were noted as the best aspects following the retrofit. No overheating was observed over the two years of evaluation. Due likely to an installation and or commissioning oversight, the MVHR system was found to be imbalanced with an inadequate extract flowrate as per building regulations. This would explain why the indoor air quality (IAQ) assessment found higher than expected CO_2 levels; 50 % of occupied hours with CO_2 concentrations greater than 1000 ppm.

In the modern dwelling, temperature was found to be well regulated and constant but higher than recommended. Primary spaces exhibited overheating; however, occupants found the home thermally comfortable with no mention of discomfort from high temperatures. RH levels are as recommended. Air quality is good; CO_2 levels were predominantly below 700 ppm, while 90 % of occupied hours were below 1000 ppm. Good IAQ was also highlighted by the user feedback surveys. The interviews revealed that the occupants leave the ventilation panel slightly open throughout the day and night since they provide adequate safety and privacy in the open position.

2.4. Occupant handover, feedback and behaviour

Handover for both homes lacked necessary explanation and demonstration of new technologies focusing rather on 'show and tell.' Both homes received home user guides which the occupants considered helpful, however upon review lacked necessary detail and illustrations in various places. Exclusions from the handover or user guide resulted in occupant's lack of understanding of control interfaces in operating low/zero carbon technologies, specifically heating. Regarding unexpected changes, in the modern home following the retrofit, two reptile tanks with warming lights, and an additional freezer were brought into the home adding to the gap in performance.

3. Discussion: gap between design expectations and outcomes

Do deep low carbon retrofits actually work? Yes and no. The 80 % target is achievable but was not achieved by a majority of RfF dwellings. According to TSB [4], three of 37 reported dwellings met the target. Though the Victorian and modern homes did not meet the target, they reduced potential consumption by over 50 % while improving comfort and satisfaction for the occupants in a number of ways. The study shows that fabric measures helped; however, occupant behaviour and expectation need to be addressed through deeper occupant engagement at all stages, so that occupants have a better understanding of the performance expectations and running of the house.

Pre-retrofit, the pre-bound gap was discovered where occupants heated the Victorian house less than expected as they knew heat would not be retained. In the modern house, the occupant's (always home) use of electricity was not properly calculated. In reality the pre-retrofit baselines made it difficult to improve upon the dwellings though much work was done to improve fabric efficiency and reduce CO_2 emissions. Unfortunately, just as the additional electrical appliances were added post-retrofit there can be no reasonable expectation that 'targets reached' means 'targets maintained.' Though comfort was achieved in the modern home it was found to be overheating at times. If new tenants move into the home with less tolerance for higher temperatures overheating will not only be a thermal comfort issue but could in the future become an additional energy issue through the use of air conditioning [11].

Main lessons learnt include: air tightness target was not achieved indicating that sealing the home for air tightness proved to be more difficult and time consuming than expected. The notable discrepancy between designed fabric expectations and outcome (air tightness and U-values) in the modern dwelling clearly indicate where the performance gap should have occurred (gas consumption); however, the greater gap was in electricity consumption due to unexpected occupant behaviour. Regarding the relative success in the Victorian home, credit is due the occupants and their pre-retrofit behaviour, stemming from their method of coping with an inefficient fabric, and general energy consciousness and interest. Alternatively, in the modern house there were greater expectations regarding warmth and comfort; 'We like to wear a thin single layer inside the house, that's the way we are.'

4. Conclusion

Most issues practitioners and academia have had to face in the RfF programme are common to all European countries [3] and it is expected that the lessons learnt in this programme will inform future retrofit efforts throughout Europe. The RfF programme was designed to target the social housing sector (representing 20 % of England's housing stock [12]) which is relatively 'homogenous' with an established organisational structure of tenants and social landlords who were able to facilitate the delivery of retrofits and select suitable tenants. The findings may not be completely representative of the private housing sector where householders have a stronger role in the decision-making process. However, considering the National Green Deal programme and the Energy Company Obligation, the findings relating to the effectiveness of mitigation measures, process and technologies are helpful in formulating packages that work best for specific house types. In the same way it is expected that these findings will inform and advance the challenge of undertaking deep low-carbon retrofit of old and modern housing in European countries.

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