Title: Do deep low carbon domestic retrofits actually work?

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Abstract: This paper uses a socio-technical building performance evaluation (BPE) approach to assess the *pre-* and *post-* actual performance of two discrete deep low energy retrofits in the UK - a Victorian solid-wall house and modern 1990s cavity-wall house. A 'low-energy first, then low-carbon' approach was adopted in both cases, to achieve an 80% reduction in annual CO_2 emissions. Pre-retrofit, both houses had lower measured annual gas consumption as compared to predictions made by energy models, although the electricity consumption in the modern house was higher than modelled, due to occupancy pattern and occupant behaviour. Post-retrofit, it was found that the Victorian house achieved nearly 75% CO_2 reduction, while the modern house achieved only 57% CO_2 reduction over the baseline emissions. Key reasons were higher than expected air permeability rates, installation issues with micro-renewable systems, lack of proper commissioning, usability of controls, occupant preferences and behaviour. Despite the gap between expected and actual carbon emissions, occupant comfort and satisfaction was significantly improved across both retrofits. This evidence-based understanding of the process and outcomes of deep low carbon retrofits is vital not only for learning and innovation, but also for scaling-up deep retrofit programmes for meeting national and international carbon targets.

Key words: Housing energy performance, deep renovation, retrofit, post-occupancy evaluation, building performance evaluation

Nomenclature:

$m^3/(h.m^2)$@50pa: air permeability rate

ppm: parts per million

$W/(m^2K)$: thermal transmittance

1. Introduction

The 2011 UK Carbon Plan [1] states that "By 2050, all buildings will need to have an emissions footprint close to zero". Specifically, the UK is legally committed to an 80% greenhouse gas emissions reduction target for 2050 and to five year carbon budgets in the interim set by the committee on climate change [1]. To meet this target, deep renovation[1] of existing buildings will be required as 28 million homes in the UK, of which 70% will exist in 2050, are responsible for about one-third of UK carbon emissions [3]. However as of the summer of 2015, in an effort to remove spending of taxpayer money from home energy efficiency, a number of policies with direct impact on energy in the housing sector have been terminated by the UK Government; the Green Deal Finance Company (ending further Green Deal[2] finance), the Green Deal Home Improvement Fund (solid wall insulation support), and Zero Carbon Homes to name a few. In addition, the RHI and FiT are considered to be at risk, i.e., further reduction in incentives for small scale renewables [5]. Though these policies were not specifically created to deliver deep renovation of housing alone, they do/ did make up the majority of the mainstream support of active energy efficiency and renewable renovation in the housing sector.

1.1 Retrofit for the Future programme and beyond

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 faced with the challenge of improving the energy efficiency of their large stock of inefficient existing housing [6]. One approach to address this issue and to support a retrofit market in the UK was the Retrofit for the Future (RfF) programme sponsored by the UK Government's Technology Strategy Board (TSB; now Innovate UK) from 2009-2013. The programme was a 'living lab' competition of many different experiments proposed to test and demonstrate innovative approaches to deep-retrofitting of the UK's social housing stock, using a whole-house approach for achieving an 80% CO_2 emission reduction target, inspired by the UK Government's

[1] Deep renovation, as often used in Europe, typically includes a focus on the building shell of existing buildings in order to achieve very high-energy performance, the improvement of technical systems such as HVAC and lighting, and the incorporation of renewable energy technologies. A deeply renovated building consumes around 75% less primary energy compared to the status of the existing building before the renovation [2]. *Note: for the purposes of this paper retrofit is synonymous with deep renovation in the sense that the whole-house approach is taken; the reduction targets are however not the same.*

[2] The Green Deal was designed to overcome the key barrier to energy efficiency uptake of high up-front costs by providing financing to install a package of measures with a facility to pay back this finance through the resultant savings in fuel bills [4].

target in the Climate Change Act. The programme 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 [7]. Almost two hundred retrofit projects across the UK were awarded funding of up to £20 000 to develop a design and implementation strategy towards meeting the target (Phase 1) and about 86 projects were awarded up to £150 000 to demonstrate the effectiveness of their strategy in reality (Phase 2) [8]. To quantify the outcome, a single CO_2 emissions target was set across the programme independent of location, building type and condition. This was done by using an estimated average emissions (1990s) baseline figure for the UK housing stock, i.e. 97 $kgCO_2/m^2/yr$ (from an $80m^2$ semi-detached house). From this figure whole house CO_2 and primary energy targets were calculated and expressed as absolute limits per unit floor area and year [8].

- CO_2 Target: 17 $kg/m^2/yr$ or 20 $kg/m^2/yr$ for projects using Passive House Planning Package (PHPP)
- Primary Energy Target: 115 $kWh/m^2/yr$

Another successful response is the Superhomes network established by the Sustainable Energy Academy. Superhomes must achieve at least 60% modelled carbon savings and the effort has been particularly successful in demonstrating materials and methods to prospective Superhome owners [9]. Beyond the UK renovation efforts are wide ranging: renZero, an industry supported (insulation, window and heat pump/ventilation producers) effort in Sweden aims to provide cost-effective deep renovation for houses built before 1980; Denmark recognises that for deep renovation to take place at the scale and pace that it must to meet targets, energy renovation needs to be done wherever any typical renovation is done; and in the French regions of Alsace and Picardie there are plans to adapt a version of the property-assessed clean energy (PACE) financing model (renovation loans attached to the property where debt is collected through property taxes; originally explored in California) to achieve deep renovation of detached housing [2]

With the current policy gap in domestic energy efficiency in the UK, options like the Netherland's *Energiesprong* and *de Stroomversnelling* (a.k.a. *Rapids)* are seen as possible solutions.

Energiesprong, for example, is a programme that works by replacing household energy bills with an *Energy Plan* that is paid to the housing provider. Similar to the Green Deal, upfront costs have to be below the savings made on energy, and with a 30-year guarantee on the performance of the measures installed. The model depends on mass retrofit whereas, if/when there is more demand, industry improves efficiency and cuts costs delivering the solution: a whole-house approach involving pre-manufactured external walls produced off-site and delivered in sections, and solar PV. The UK's Energy Saving Trust is involved in exploring integration of the programme into the UK housing market [10]. There is also discussion of exporting the *Rapids* approach to the UK and France. The initial difficulty involves adjustments to both the technology and the business model, as housing types and the structure of the housing market are very different in each country [11].

1.2 The retrofit performance gap and building performance evaluation

A large number of international modelling studies, such as in Argentina [12], Belgium [13], Germany and The Netherlands [14], Kuwait [15], and USA [16] have demonstrated that energy and environmental performance of existing buildings can be improved through appropriate retrofit methods; however, actual energy savings due to the implementation of retrofit measures in real buildings can be different from those estimated [17]. The following study, along with the RfF programme, defines this difference as the performance gap, i.e. the significant difference between the calculated forecasts for energy use compared with the actual energy use [7].

Though less research exists, plenty of examples demonstrate this performance gap. Results published for the overall RfF programme revealed that among 24 dwellings, a majority measured actual energy use to be 50% more than predicted. Only four cases were marginally off (by 5%). An important lesson learned from these projects is that projects that forecasted lower energy use were likely to achieve lower results relative to other projects even if the outcome was not as low as forecasted [7]. Following the Warm Front Scheme in the UK from 2001-2003, 1372 dwellings were retrofitted with cavity wall and loft insulation and new central heating systems. Savings were calculated to reduce fuel consumption by 49% but monitoring revealed savings of only 10-17% and thermal imaging on a sample of dwellings revealed large gaps in insulation [18]. Galvin [19] presents a wide range of results for three retrofitted residential buildings in Germany. These case studies were found to consume 0.02%, 36%, and 73% more heating energy than calculated during design. These studies present valuable insight into a large evidence base for the retrofit performance gap but do not outline the BPE level of detail for individual case studies.

In contrast at case study level, research appears to be more focussed on pre- vs. post-retrofit results excluding modelled results. As examples, a dwelling in Saudi Arabia was retrofitted with four energy conservation measures: external wall insulation, draught proofing around doors and fresh air intake panels (neutralising the building pressure), and ventilation system balancing. The study however focussed on pre-retrofit and post-retrofit energy consumption data with no mention of designed energy reduction calculations or expectations. The dwelling resulted in an 8% increase in total electrical energy consumption comparing six years of pre-retrofit data to six years of post-retrofit data, but realised a 21% mean reduction when comparing the summer peak months of both periods. The smaller overall increase is likely a result of the difference between the two families that lived in the dwelling over the course of the study and their ‘significant difference’ in user profiles, family size and appliance use [20]. An unoccupied research dwelling in the USA was evaluated following a fabric and duct air tightening retrofit. Evaluation included tracer gas decay technique and whole building pressurization testing using a blower door. The tests showed an envelope leakage reduction of 18% and duct leakage reduction of 80% resulting in an overall energy consumption reduction of 10% after ‘several months’ of monitoring [21]. Another research house in Nottingham, England was retrofitted with improved external wall, floor and glazing, and upgraded heating system efficiency, a whole-building mechanical ventilation with heat recovery (MVHR) along with increased air tightness. The analysis of the dwelling included building performance simulation to determine the combined effects of the retrofit package on indoor air psychrometric conditions, external envelope heat transfer, operational energy efficiency, occupant comfort, and mould growth potential. Thermal comfort and measured heat transfer was found to be improved following retrofit; however, the performance gap with regard to energy consumption was not assessed [22].

Because the RfF programme encouraged experimentation of new materials, methods and systems, building performance evaluation (BPE) was used to analyse the effectiveness of processes and outcomes. Retrofitted buildings can also be victim to the trend of evidence-less claims for ‘high performance' or 'sustainable' retrofits. As any country begins to scale up retrofitting to meet local, national or international regulations or targets, it is clear that BPE is a promising and arguably essential element for meeting these targets. BPE will be a useful approach for upcoming policies or programmes similar to any of those mentioned above as it is useful for establishing whether targets are delivered and can be useful for experimenting with and understanding how business models, methods, and technology can be transferred between countries. Among numerous benefits, BPE has the capacity to provide quantifying (through monitoring and verification) and delivering return on investment and/ or reducing risk, e.g. improvement in environmental conditions that have occurred as a result of retrofitting, reduced energy, utility bills, and CO_2 emissions and contextualised performance outcomes; detailed, experienced hypotheses that can be applied in future buildings [23].

It is within this context, this paper comparatively evaluates process and performance from a technical and users' perspective for two case study dwellings (a Victorian solid-wall end-terrace and a Modern 1990s cavity-wall mid-terrace) in the UK, on which an occupant-centred longitudinal, over two year, BPE approach has been applied in order to achieve ambitious and whole-house low-carbon retrofits. This research differs from previous work in that it addresses the physical and social elements through in-depth evaluation of two living case studies which had detailed POE before and after retrofit. The lessons learned will help inform the process of providing mass retrofits.

2. Methodology

For the RfF programme, the requirement for each retrofit was to use a 'whole house approach' to meet the CO_2 target and to include a comprehensive post-retrofit monitoring strategy in accordance with TSB specifications [6]. In addition to those requirements every project had to perform pre- and post-retrofit air permeability tests and thermography studies, and post-retrofit PCRs and occupancy surveys [8]. As-designed emissions targets were assessed using a modified version of the Standard Assessment Procedure (SAP) or Passivhaus Planning Package, where applicable.

2.1 Case study dwellings

Two case study retrofitted dwellings, a Victorian solid wall end-terrace dwelling built before 1919 and a modern cavity wall mid-terrace dwelling built in 1992, are the subjects of the present study. As the only stipulation for dwelling selection placed on the RfF programme was that the selected dwellings be in the social housing sector, the dwellings were selected by the local authorities in communication with the architects responsible for the retrofit design [24]. Table 1 provides pre-retrofit characteristics of the dwellings; figures 1 & 2 show the facades of the dwellings (post-retrofit).

Table 1 Details of the original constructions

	Victorian dwelling	**Modern dwelling**
Location	London	Oxford
Year built	Pre-1919	1992
Built form	End-terrace	Mid-terrace
Area	76.9 m^2	84 m^2
Occupancy / bedrooms	2 adults / 2 beds	2-4 people (varies) / 3 beds
Orientation (front façade)	Southwest	Southeast
Original construction	Walls: solid brick Roof: timber trussed slate roofed Ground floor: concrete ground floor slab Windows: uPVC double-glazed	Walls: masonry cavity Roof: pitched tiled roofed Ground floor: concrete ground floor slab Windows: uPVC double-glazed
Observations	Uninsulated fabric, difficult to attain comfort temperatures, poor indoor air quality, poor levels of daylight, excessive use of tumble dryer	High occupancy related electricity demand, heat loss at windows, front door and party walls, poor indoor air quality
Ventilation	Natural ventilation	Natural ventilation

Figure 1 Victorian dwelling post-retrofit – front (left) and rear (right) facades

Figure 2 Modern dwelling post-retrofit – front (left) and rear (right) facades

2.2 Pre-retrofit

Supplementary to TSB requirements mentioned above, the specific methodology developed for the evaluations of the two dwellings in this study included pre-retrofit POE. Table 2 shows the pre-retrofit timeline, data collected and the corresponding methods. Data was collected through site visits, collection of energy bills, meter readings and occupant questionnaires and interviews. Fuel bills for one year for both gas and electricity were analysed to understand energy use in the dwellings. A SAP 2005 analysis was also carried out to assess the difference between actual and modelled results. SAP is the UK government's Standard Assessment Procedure for Energy Rating of Dwellings. It is a steady-state calculation method used to demonstrate building regulations compliance for dwellings. SAP was developed from the UK Building Research Establishment's Domestic Energy Model in 1992 [25]; the 2005 version was extended to ensure compliance with the Energy Performance of Buildings Directive and to enable its use for regulations and energy performance certificates [26]. Environmental conditions of the dwellings were also measured for two months through the use of data loggers and spot measurement devices. Pre-retrofit evaluation was used to ascertain in-use characteristics and identify appropriate interventions for retrofitting. The evaluation also helped establish actual project specific baseline performance and a reference point to which occupant behaviour and patterns could be compared. More information on the pre-retrofit process was covered in Gupta and Chandiwala [24] (note that not all post-retrofit methods planned and reported in this source were carried out such as the co-heating test because of the disruption and inconvenience that it would have caused for the occupants).

Table 2 Timeline, data collection and methods used in pre- and post-retrofit stages

	Data collected	**Method**
Pre-retrofit August – November 2009	Basic building data/existing conditions, e.g. built form, built age, existing systems	Pre-retrofit assessment through site visits, photographic survey, access to as-built drawings developed by architects
	Air permeability (baseline)	Blower door test, trickle vents closed, water traps filled, windows closed, bathroom and kitchen extract sealed with tape, internal doors open; testing and calculations in line with the Air Tightness Testing & Measurement Association's Technical Standard for dwellings [27]
	Fabric condition	Thermal imaging
	Pre-retrofit energy consumption and CO_2 emissions: modelled and actual (baseline)	Pre-retrofit monitoring and feedback, heating schedule logging sheet, consumption data collected through energy bills and periodic meter readings / SAP modelling
	Environmental conditions: internal and external temperature, relative humidity, daylight, CO2 levels, water consumption, opening/closing of doors and windows	in-use monitoring with data loggers and spot measurement devices; Hobo and I-button data loggers set to measure at fifteen minute intervals
	Occupant behavior and opinion	Occupant satisfaction questionnaire, open-ended semi-structured interviews, appliance energy-usage questionnaire, thermal comfort questionnaire

2.3 Retrofit design and construction

Both projects followed a 'fabric-first' i.e., 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.

2.4 Post-retrofit

Following the completion of the retrofit, a two-year BPE study was conducted which included continuous remote monitoring of environmental parameters (indoor and outdoor temperature, relative humidity (RH) and CO_2 levels), smart metering of energy consumption cross-related with regular feedback gathered from occupants through questionnaires, interviews, walkthroughs and activity log sheets. To assess the post-retrofit CO_2 performance, two years of electricity and heating fuel energy data were collected and normalized using floor area and common CO_2 metrics. Table 3 shows the stages, timeline, data collected and the corresponding methods.

Table 3 Timeline, data collection and methods used in pre- and post-retrofit stages

	Data collected	Method
Post-retrofit early occupancy **March 2011 – Oct. 2011**	Air permeability	Blower door test, trickle vents closed, water traps filled, windows closed, bathroom and kitchen extract sealed with tape, internal doors open; testing and calculations in line with the Air Tightness Testing & Measurement Association's Technical Standard for dwellings [26]
	Fabric condition (including In-situ measurement of thermal resistance and thermal transmittance.)	Thermal imaging U-value measurements: Hukseflux HFP01 sensors on north facing walls using the "Average method" detailed in ISO 9869:1994 [28]
	Handover evaluation	Observation, photographic survey & questionnaire / interview
Post-retrofit in-use **March 2011 – March 2013**	In-use monitoring: Energy and environmental data: • Meters for gas, electricity, water, PV and solar thermal with remote data collection • Internal temperature and relative humidity in three locations - living room, hall and principal bedroom • External temperature and relative humidity • Indoor air quality:CO_2 (as a proxy for overall air quality) and window opening patterns • MVHR intake and exhaust temperatures	Long-term monitoring through installed monitoring equipment
	Feedback: Occupant experience with the installation process/ how the occupant(s) is interacting with the measures/occupant thermal and overall comfort	Occupant satisfaction questionnaire, open-ended semi-structured interviews, appliance energy-usage questionnaire, thermal comfort questionnaire
	End of study air permeability	(Same as above)
	End of study fabric condition	Thermal imaging

3. Pre-retrofit building performance evaluation

3.1 Pre-retrofit findings

A significant innovation for the RfF projects was the inclusion of pre-retrofit in-use monitoring and occupant feedback to understand how the house performs physically and the effects of occupant requirements and behaviour on the energy use within the house. All proposed 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 [24].

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.

As a result, the actual gas consumption was half that of the SAP estimated consumption (figure 3). Though the gas consumption does not appear to be large, in reality the greater problem, which can be met through the same solutions, is the need to provide comfort and affordable heating in the hard to heat, hard to treat condition of the solid wall Victorian home. Indoor air quality (IAQ) monitoring revealed CO_2 levels averaging around 1300ppm, a finding that inspired the integration of mechanical ventilation into the retrofit. 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 and ventilation.

In the Modern home, the almost full time, high occupancy density (four adults in an 84 m^2 home) resulted in an electricity demand significantly higher than that estimated by SAP (figure 4). Given the high amount of electricity use (almost three times SAP estimated) and the associated CO_2 emissions, particular attention was given to occupant behaviour and reduction of electricity use in the house was considered a key area for retrofit. 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 meeting the programme's target. Thermal imaging helped identify the areas of heat loss which included; the windows, front door and the location where the party walls extend above the roof. The identification of the party walls as an area of heat loss was particularly useful because this had not been considered before.

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 [6]. Therefore, it was expected that the Victorian home would consume more energy and be more difficult to retrofit than the modern home. In reality the Victorian home was consuming less pre-retrofit gas and electricity than the modern home (figure 3 & 4). 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 what was assessed through occupant questionnaires and energy use analysis as the pre-bound effect [29]. *Note: the following conversion factors are used for CO_2 emissions throughout the paper: gas = 0.184; electricity = 0.525* [30].

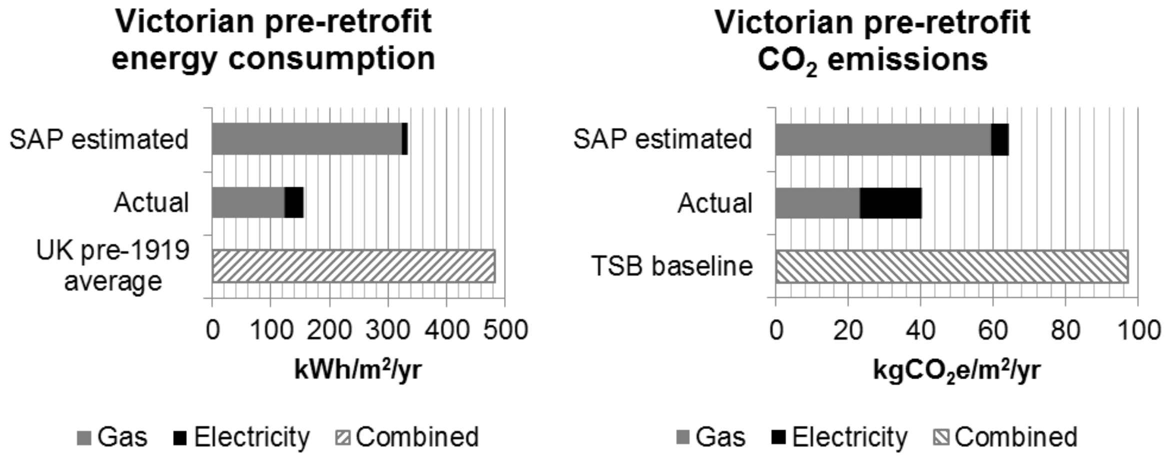

Figure 3 Pre-retrofit energy consumption (left) and CO_2 emissions (right)

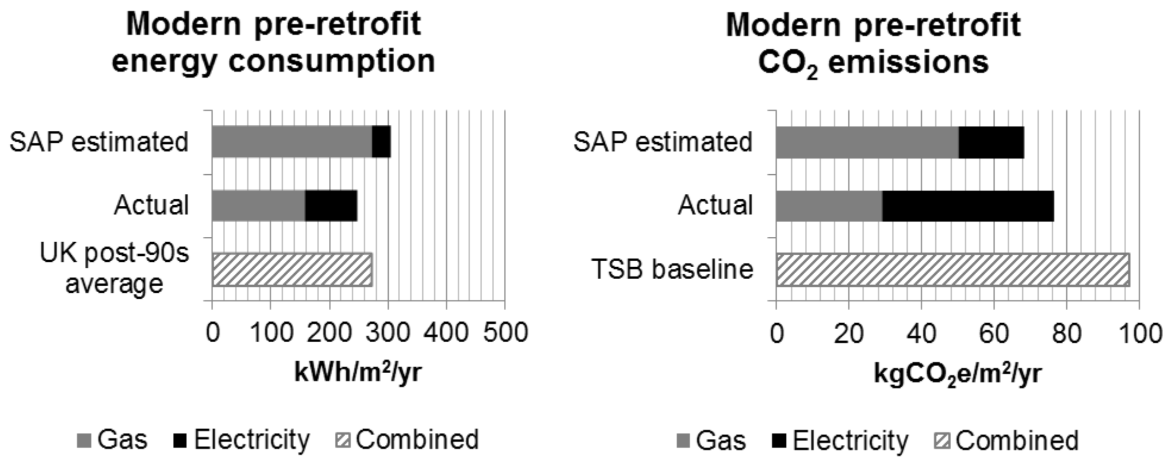

Figure 4 Pre-retrofit energy consumption (left) and CO_2 emissions (right)

4. Retrofit design and process

Retrofit interventions are detailed in table 4.

Table 4 House and retrofit details

Retrofit elements	Victorian dwelling	Modern dwelling
Fabric improvement (with stringent U-values and minimal thermal bridging)	• External, cavity and internal wall insulation, floor vacuum insulation and loft insulation • Triple glazing windows	• Cavity insulation and external insulation, floor vacuum insulation and loft insulation • Triple glazing windows

	• Increased air tightness	• Increased air tightness
Systems upgrade / systems, appliance & lighting energy reduction	• High efficiency boiler, • A++ appliances, • LED lighting • Redesign of living space and bathroom for daylight • Addition of skylight, • Passive clothes drying space	• High efficiency boiler, • A++ appliances, • LED lighting • redesign of loft space for daylight • Addition of roof-light • Passive clothes drying space
Renewable systems	Solar PV & solar thermal	Solar PV & solar thermal
Ventilation	Mechanical ventilation with heat recovery (MVHR)	Natural ventilation
Retrofit experience	Decanted	In situ

The original exterior façade of each dwelling was preserved through the use of internal and cavity wall insulation (figures 1, 2 & 5); external solid wall insulation was installed on the rear. The ventilation strategies were different; a MVHR system was proposed to ensure good levels of IAQ for the elderly occupants in the Victorian terrace. The modern home was retrofitted with built-in, secure, louvered, ventilation panels on the two levels and an automated roof-light (figure 6). 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 stayed in the dwelling through the process. 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, both dwelling's occupants found the retrofit process inconvenient.

Figure 5 Front façade of Victorian house before (left) and after retrofit (right)

Figure 6 Modern house triple glazed windows with side ventilation panels (left) and automated roof-lights (right)

5. Post-retrofit BPE

Post- retrofit, the fabric performance of the dwellings were assessed, the occupant handover was evaluated and a two year monitoring and evaluation study was conducted which included continuous (in-use) monitoring of various environmental parameters (temperature, humidity, CO_2) in key spaces, smart metering of energy consumption cross-related with regular feedback from occupants through questionnaires, interviews, walkthroughs and activity log sheets.

5.1 Early occupancy stage

The early occupancy stage included testing of building fabric and evaluation of handover to investigate the communication of design intent to users as to how to operate their home.

5.1.1 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 airtightness detailing and its impact on the performance of the building. Though the above effort was taken, the target was not achieved (table 5); 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 [31]. MVHR, where unnecessary, can be both a costly intervention (average cost of £6 117 (€7 686) in the RfF programme [32]) 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 [33]. The modern home aimed to achieve the lowest air permeability allowed without requiring whole house ventilation (table 5); 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. Unfortunately post-retrofit, the final air permeability was higher than pre-retrofit in the modern dwelling.

Table 5 Air permeability results

	Victorian	Modern
Pre-retrofit air permeability ($m^3/(h.m^2)$@50pa)	5.9	5.7 (mean of two tests)
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 tests)	6.5 (mean of two tests)
Air perm. rank among all 86 RfF projects	32	60

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) (figure 5 & 7). Much greater thermal consistency was seen on the back of the property where external insulation was used throughout (figure 1).

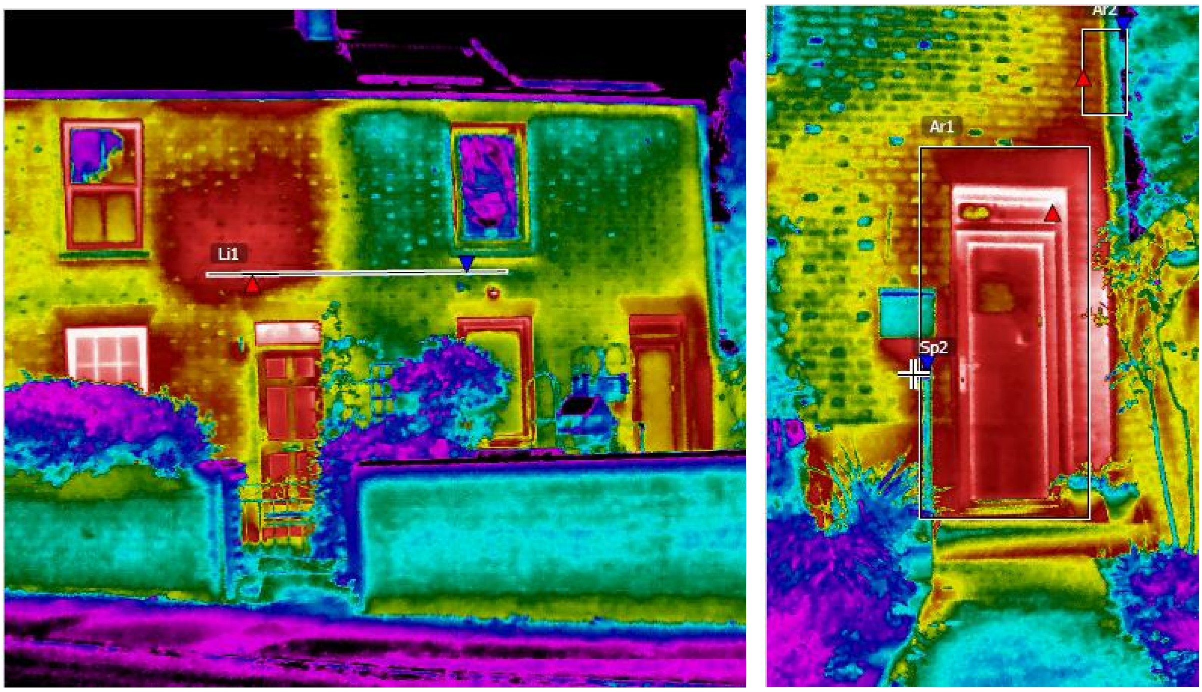

Figure 7 Thermal images of the front façade of the Victorian house showing the contrast between neighbouring properties (left) and the junction where external insulation on the end wall meets the front façade with internal insulation (right)

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^{2}K)) than the as-designed U-value (0.135 W/(m^{2}K)) and on the south the U-value was lower (0.11 W/(m^{2}K)), 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^{2}K)) were greater than the target U-value (0.15 W/(m^{2}K)).

5.1.2 Handover evaluation

The handover process is an important step in communicating the significance of the measures taken and operation of particular features which may or may not be typical. These features include the operation and maintenance of MVHR, e.g. changing filters and operation of user interfaces, e.g. heating controls. Efficient use by occupants directly impacts the energy use of the home. The handover process is accompanied by a home user guide which documents the information provided to the occupants. 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. Lessons learned from the handover include:

- Objectives, process and time required should be clarified in the beginning and the overall intent of the monitoring study explained so that the occupant can remain engaged in the whole process. (Allow at least 90 minutes to explain all aspects of the house.)
- It would be helpful for the tenant to have their tenant liaison officer present, so that s/he could familiarise themselves with the house and support any potential trouble-shooting.
- Carefully co-ordinate the tour with the written guide and make sure the tenant is following the descriptions in the guide as the tour progresses. This helps the occupant make visual connections between the guide and the actual equipment for future reference.
- Encourage the tenant to try out technology functions for themselves as they are explained rather than just demonstrating them.

5.2 In-use stage

5.2.1 Final energy assessment

Post-retrofit, it was found that the Victorian house achieved a 75% CO_2 reduction while the modern house achieved only 53% CO_2 reduction as compared to the retrofit programme baseline. Neither dwelling met the 80% reduction target. Reductions from actual existing pre-retrofit baselines were actually lower, i.e. around 40% for both dwellings (figure 8). The reduction percentages are the mean of two years (2011 & 2012) of energy data collected for each project. Figure 8 shows both years of energy data and the mean of the two years.

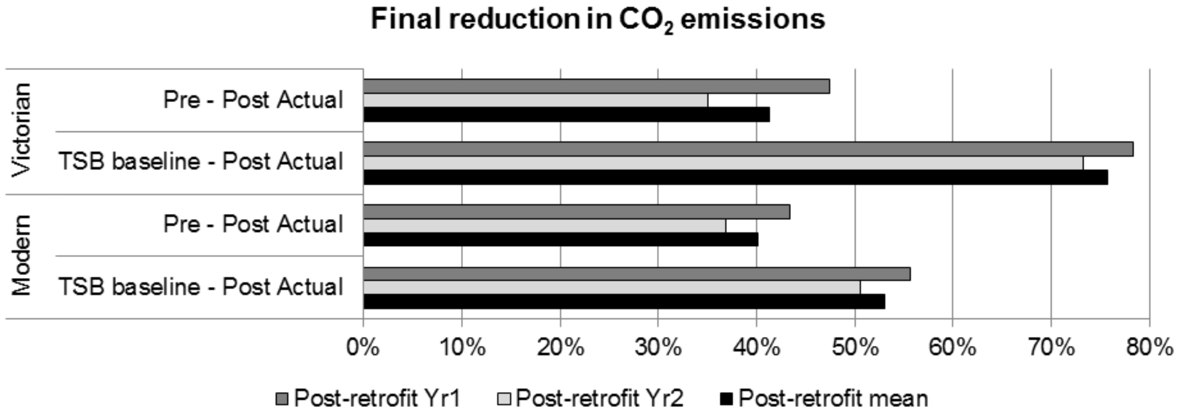

Figure 8 Post-retrofit reductions in CO_2 emissions.

Figure 9 shows the two dwellings among a select number of RfF projects for which final CO_2 emissions figures are available. Of 52 projects the Victorian dwelling (D14) ranks 14 and the Modern dwelling (D36) ranks 36. Four dwellings met the target.

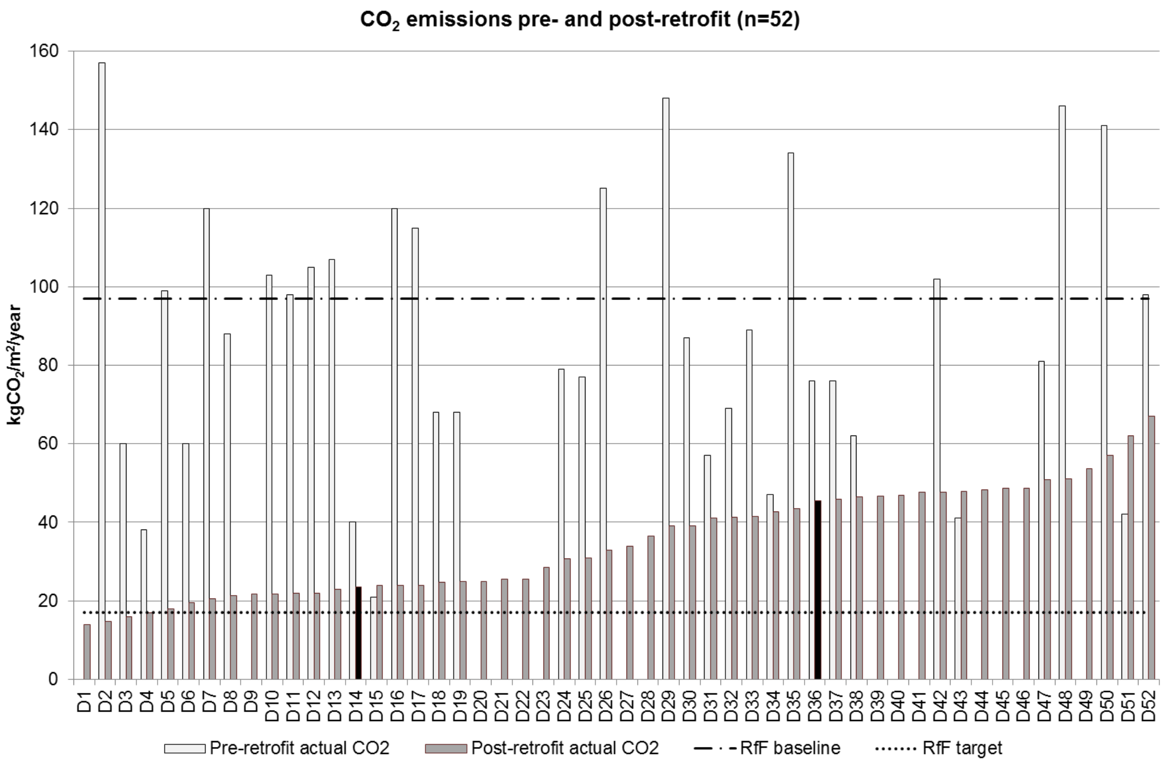

Figure 9 Pre- and Post-retrofit CO_2 emissions for a select number of RfF projects [6, 34, 35]

Both households increased emissions (heating and unregulated; though mostly heating) in the second year of occupancy (figure 10). The presented data is not weather corrected; however, the increase in consumption over the second year is attributed to colder weather experienced in 2012 (26%, Oxford & 27%, London increase in Heating Degree Days in 2012 over 2011). When gas consumption is normalised for the weather for the two years in both dwellings, both dwellings actually used less energy than expected in the second year, whereas the first year was slightly higher. For the Victorian dwelling mean actual annual energy consumption is below the post-retrofit predicted but because actual electricity consumption is much higher than predicted electricity consumption, the carbon emissions are higher as the emissions from electricity are greater.

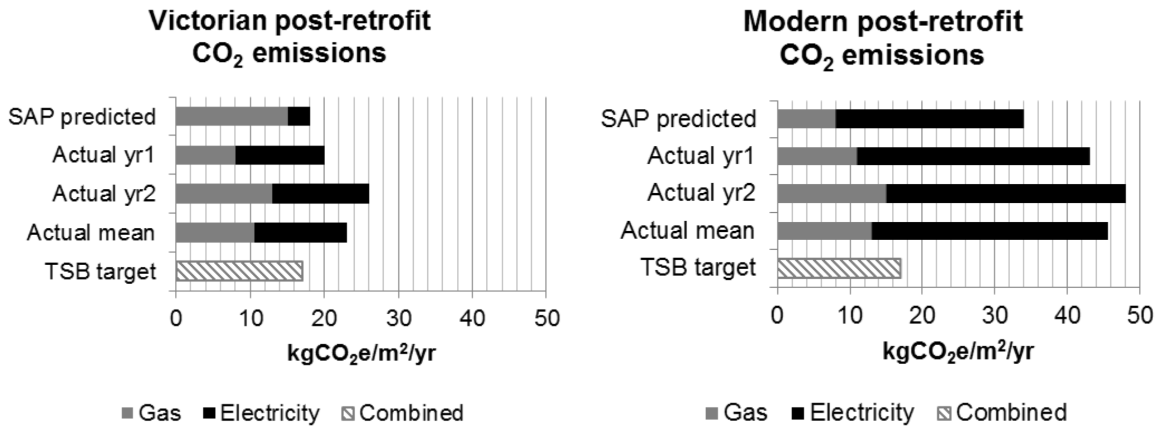

Figure 10 Post-retrofit CO_2 emissions, Victorian dwelling (left) and Modern dwelling (right)

Electricity consumption has been the most problematic to predict. Though the Victorian home was successful in consuming less gas than predicted, actual post-retrofit electricity consumption was four times what was predicted. The graphs in figure 11 show the steep slope of the SAP estimated indicating the ambition of the programme. For the Victorian dwelling the slope was not as steep in reality as the pre-retrofit actual emissions were significantly lower than estimated and the post-retrofit emissions were not as low as targeted. For the Modern home, the CO_2 emissions gap in reality was relatively proportionally in line with modelling estimations both pre- and post-retrofit. The figure's pre-retrofit performance gap reflects a common finding across Europe that generally, new dwellings have higher energy consumption than expected and older dwellings have lower consumption [36]. With regard to SAP in particular, the assumed demand temperature for living areas of 21^{o}C may not apply to older dwellings [3]. This was especially true in the Victorian dwelling.

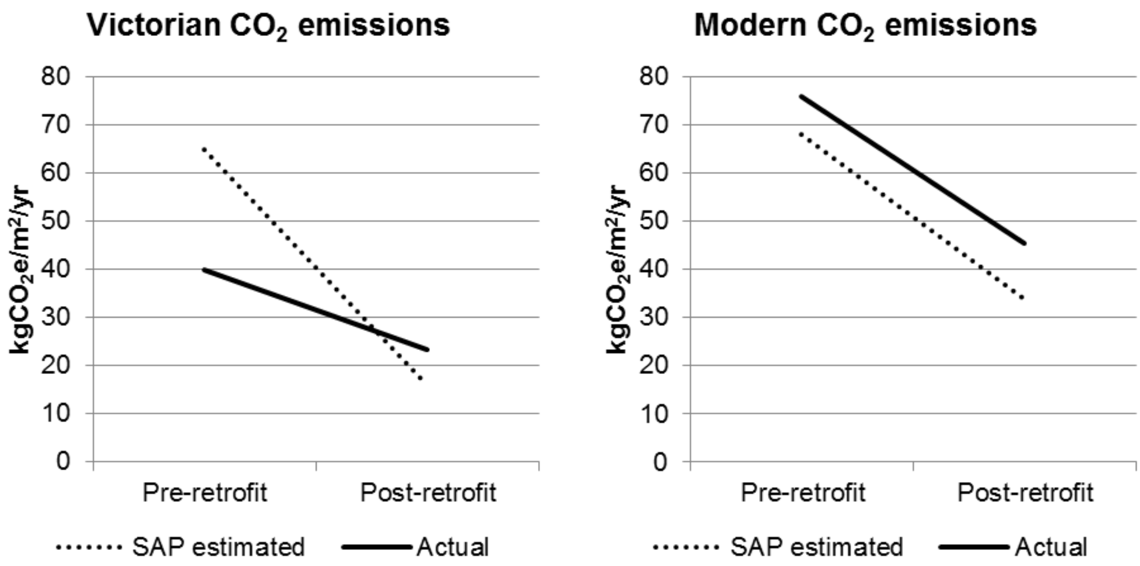

Figure 11 Pre- and post-retrofit CO_2 emissions, Victorian dwelling (left) and Modern dwelling (right)

5.2.2 Environmental performance

Post-retrofit, the Victorian home exhibited steady and satisfactory temperature and RH levels (according to design guidance [37]) 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 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, temperatures were 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 and IAQ 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. As the occupants are smokers, this is a significant improvement in ventilation capability over pre-retrofit conditions. Figure 12 indicates that the ventilation panels are effective, however, obviously as they cannot be used as often in the winter the highest CO_2 concentrations are in winter.

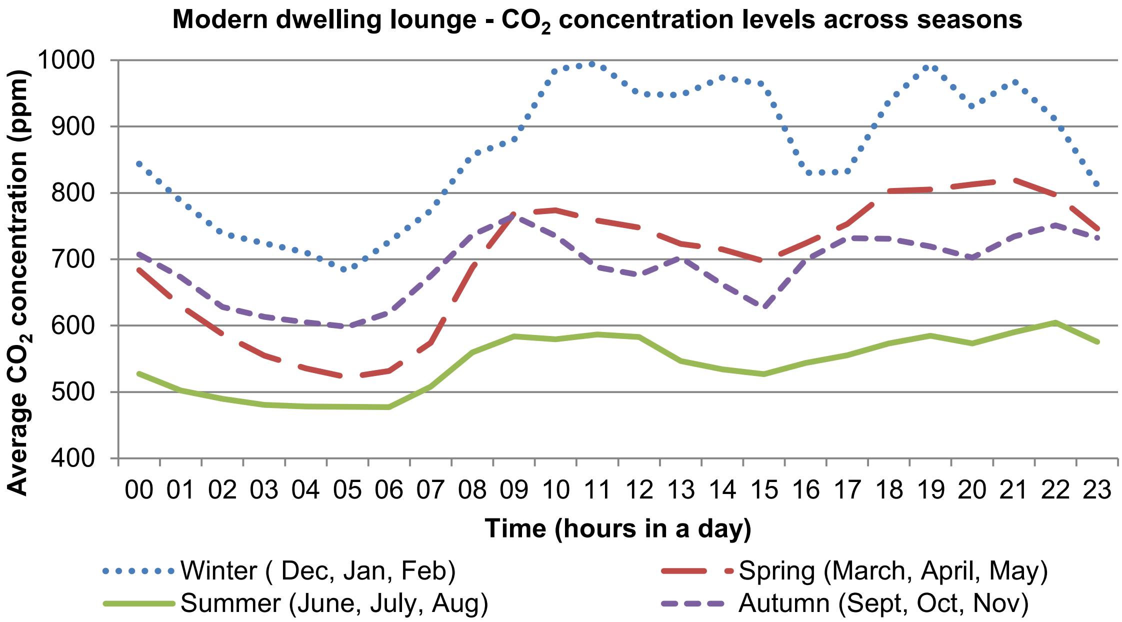

Figure 12 Modern dwelling average hourly CO_2 concentrations in the lounge across seasons

5.2.3 Occupant feedback and behaviour

The occupants of the Modern house expressed their preference not to spend time learning how the new systems work (e.g. the thermostat) and would rather adopt easy and 'uncomplicated' ways of controlling the installed systems. In addition, the occupants do not keep track of energy bills and have the incorrect perception that there are no savings. Regarding unexpected changes, occupant expectations do not match retrofit objectives, as examples, the occupants of the modern home purchased a new 'unrated' freezer, frequently uses the dryer, and added two reptile tanks with warming lights adding to the gap in performance. Table 6 lists the best and worst aspects from the occupant's point of view before and after retrofit.

Table 6 Best and worst aspects before and after retrofit

		Best aspects	**Worst aspects**
Victorian	**Pre-retrofit**	Garden, location, house character and summer thermal comfort	Lack of daylight, small rooms, lack of storage
	Post-retrofit	Extra daylight, no draughts, temperature control and responsiveness, noise reduction, less dust	Lost storage space (lost second bedroom to displaced storage; water temperature issue with bath.

Modern	**Pre-retrofit**	Nice garden, very good location, spacious kitchen, location, great daylighting in the rooms, good-sized living room	Generally small bedrooms; lack of storage space; landing on the first floor is a waste of space
	Post-retrofit	The new windows and the loft conversion have been very satisfactory.	Issues with the electrical wiring; appliance blow out and the fuse trips very often.

The occupants of the Victorian home continued to practice pre-retrofit behaviours which include avoiding use of lighting whenever possible, closing off lounge from the rest of the house during the heating season, wearing more clothing when cold, not opening the windows when heating, and not leaving appliances on standby. In addition, newly adopted behaviours include washing when solar PV output is perceived to be highest, rarely using the tumble dryer and turning off the gas boiler's supplementary heating at night if the solar thermal heating level is deemed sufficient for their expected hot water needs in the morning.

6. Discussion

At any stage of a domestic retrofit (from modelling to design and construction through to in-use), difference(s) between intent and outcome can surface. This performance gap can result in a significant overall difference in energy performance from that expected, thereby increasing fuel costs for residents. In the case of the Modern dwelling, the high density and almost full-time occupancy meant that the electricity demand was significantly higher than that predicted by the energy model. By understanding appliance use and occupant behaviour at the pre-retrofit stage, this gap in electricity prediction could be minimised. The significant difference found between modelled and actual carbon emissions (table 7) of the retrofits, indicates that it is important to calibrate energy models with real data on energy and environmental performance.

Table 7 Summary of results

Retrofit elements	Victorian dwelling	Modern dwelling
Performance gap (difference in actual and predicted post-retrofit CO_2 emissions)	+28% greater than predicted	+34% greater than predicted
Fabric improvement: Post-retrofit air permeability ($m^3/(h.m^2)$@50pa)	3.5 greater than target of 1	6.7 greater than target of 3
Fabric improvement: U-value measurements ($W/(m^2K)$)	Mean U-value 0.135 on target	Mean U-value 0.285 almost 2x target
Environmental and ventilation	Good, steady temperature and RH; imbalanced MVHR, high CO_2	High temperatures and good RH; good CO_2
Retrofit experience	Retrofit process unsatisfactory and inconvenient; highly satisfied with thermal comfort and daylight levels	Retrofit process unsatisfactory and inconvenient; satisfied with thermal comfort

During construction and commissioning, the fabric measures were effective to some degree; however, in the Modern dwelling, U-values were lower than expected which could likely contribute to the gap in gas consumption figures. This can be a result of poor planning and communication resulting in improper installation of insulation and thermal bridging, and the fact that the builders had to work around the residents, who occupied the Modern dwelling during the retrofit. Similarly, another retrofit project reported that because residents were in situ, airtightness measures were not fully completed due to the inability to seal around intermediate floors in the dwelling [7].

Another area likely to be contributing to the performance gap is airtightness. There was a notable difference in the designed and actual air permeability rates for both dwellings. This was particularly disappointing in the Victorian dwelling as much effort was made to meet a strict standard. The airtightness target was not achieved indicating that sealing the home proved to be more difficult and time consuming than expected. In the case of the Modern dwelling, because low air permeability was not central to the naturally ventilated retrofit, possibly 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. The heat loss indicated by thermal imaging on the front right corner of the Victorian dwelling demonstrates a likely contributor to the performance gap indicating the unintended consequence of working with protected facades. These issues highlight the importance of mid-construction testing through methods such as air pressure testing and thermal imaging [33, 38].

The performance gap can also arise from installation and commissioning issues. In the Victorian dwelling, after monitoring showed high CO_2 concentrations, the MVHR system was found to have been commissioned with inadequate extract flow. Unbalanced MVHR systems after installation and commissioning are apparently a common issue in new build and retrofitted dwellings [33, 38, 39]. A commissioning fault was also found with the PV installed on the Modern dwelling. Because of this savings were lost for a period of time. Interestingly without such a BPE-based approach, these underperformance issues in the deep retrofits, would not have been discovered, and could have developed into more serious issues.

During the in-use phase occupants that are not properly prepared or informed, and/ or firmly attached to certain behaviours can contribute to the performance gap. Occupant behaviour and expectation need to be addressed through deeper occupant engagement at all stages and thorough, appropriately scheduled handover and hands-on training,with follow up so that occupants have a better understanding of the performance expectations and running of the house. Regarding the relative success in the fabric improvement of the Victorian home, credit is due to 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.’ In the Modern house the heating system was also incorrectly operated out of convenience; though proper operation was explained. This reveals that although the retrofit was successful in reducing fuel consumption through improved fabric and systems, it has not been able to influence user behaviour. Though there is a notable discrepancy between designed fabric expectations and outcome in the Modern dwelling, the more surprising gap occurred regarding electricity consumption due to unexpected occupant behaviour. As an example, the occupant claimed they preferred to use the dryer instead of the built in drying space because the dryer was more convenient. Unfortunately, just as the additional electrical appliances were added post-retrofit, there can be no reasonable expectation that ‘targets reached’ means ‘targets maintained.’ Though from the occupant’s perspective, comfort was achieved in the Modern home, it was found to be technically 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 [40].

Do deep low carbon retrofits actually work? The answer can be yes or no depending on who is asked and what their expectations are. The 80% target is achievable and was met by a few projects in the RfF programme, though it was not achieved by a majority of the dwellings [41]. Even when they do not go as deep as expected, deep low carbon retrofits do work because, though the case study dwellings did not meet the target, they reduced actual consumption by around 40% while improving comfort and satisfaction for the occupants. The most commendable example is through the improvement of the ‘difficult to heat’ solid wall Victorian home. The retrofit resulted in real gas consumption reduction of 55% whilst at the same time enabling the occupants to achieve thermal comfort and experience a significant reduction in energy costs. Unfortunately however, given the cost of deep retrofits [33], the apparent performance gap and the current political trajectory regarding government funding and support of energy efficiency in housing, it appears unlikely at this time the housing sector can meet UK's carbon reduction targets. Nonetheless, it is vital to identify and understand where the performance gap can occur within the retrofit process, as deep retrofit programmes are launches. For example, in programmes such as Superhomes, *Energiesprong, de Stroomversnelling,* or similar, the success of the retrofits and an entire retrofit programme will depend significantly on the real savings in energy bills to cover the cost of the measures.

7. Conclusion

The RfF programme was designed to target the social housing sector (representing 20% of England's housing stock [44]) 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, the findings relating to the effectiveness of mitigation measures, process and technologies are helpful in identifying where the performance gap could lead to problems in any retrofit and advance the challenge of undertaking deep low-carbon retrofit of old and modern housing in European countries.

This is why most issues faced in the RfF programme are common to all European countries [6] and lessons learnt from this programme could inform future retrofit efforts throughout Europe. Where the energy efficiency policy void could potentially be filled with private sector programmes like *Energiesprong* or *de Stroomversnelling* that use pre-fabrication for specific house types to streamline process, speed and cut costs [10, 11], it is apparent through the case studies that the retrofits would benefit from, and likely to avoid in-use performance gaps by applying a holistic process involving occupant education and support. In dwellings where occupants preceded and are expected to remain, retrofit programmes would also benefit from pre-retrofit BPE to understand occupant expectations and behaviour. More importantly learning from BPE can support the innovation required for scaling up of deep retrofit programmes, wherein lessons learnt can be passed on from one to the next, and the gap between intent and outcome can be reduced.

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