PRP

Dartford Housing Retrofit Project

Evaluation Report

July 2017

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Author	Jenny Ho and Sara Celentano
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Executive Summary

1. PRP on behalf of Innovate UK oversaw the retrofit of ten semi-detached homes in Dartford to a very high standard as part of the 'Scaling up Retrofit' project. A detailed analysis of four of these ten households was commissioned by the Department for Energy and Industrial Strategy (BEIS). The data presented in this report shows that significant benefits, in terms of comfort, bills and CO_2 emissions were seen by the four households studied in detail, which suggests the project as a whole was successful in delivering good quality retrofits to hard-to-treat properties which delivered real results while maintaining quality and avoiding adverse consequences associated with poorly-fitted retrofits.

The 'Scaling up Retrofit' project took a holistic approach in delivering retrofit solutions with particular focus on technical solutions that tackle thermal bridging issues. The aim of the project was to test and validate the desktop-developed process that can deliver the residential retrofit at lower cost, less site time with minimum disruption to the occupants while achieving a significant reduction in energy consumption and CO_2 emissions. The wider aim of the project was to develop the commercial offering through the iterative process and to assess the viability of delivering retrofit at a larger scale.

An evaluation of the social and environmental benefits of the retrofit was undertaken from the data collected from the four homes which was retrofitted as part of the 'Scaling up Retrofit', as detailed in this report.

The responses from the occupants indicated that they were generally very happy with the improvement to their houses after the retrofit works were undertaken, in terms of comfort and the appearance of their property. Our analysis from the environmental data showed an improvement of the internal environment of these homes post-retrofit. In particular, issues of mould growth and the risk of condensation were addressed and good air exchange was maintained.

The study demonstrates that there is a trade-off between personal comfort and energy consumption. Energy bill data were available for all four homes in the project and two saw significant reduction (-19% and -32% respectively) in consumption post-retrofit. One other saw a slightly lower reduction (-13%) in consumption but the home was significantly warmer post-retrofit, and it was confirmed at the interview that the occupants were unable to heat the home as they desired prior to retrofit. Occupant choice to have a warmer home has therefore led to a smaller reduction in consumption in this home. Only one of the four homes showed little variation in consumption pre and post-retrofit; however, it was clear from the evaluation that this was largely due to the fact that gas consumption in this home was low before retrofit, due to small dwelling size and the occupants manually controlling their heating system, only turning it on when required. The low level of consumption made it impossible to derive a statistically significant change (i.e. any change in consumption pattern was lost in the noise due to different weather conditions, occupancy patterns etc.)

It can be deduced from the study that further reduction in energy consumption can be achieved simply by increasing the occupants' awareness of the heating controls, and of their understanding on how some of their habits (such as window opening, which was observed during the study to be a commonly used way to control internal temperatures and/or provide ventilation) could potentially have an impact on the energy savings.

The 'Scaling up Retrofit' project has demonstrated that a residential retrofit can be delivered at the average cost of £16,000 through a holistic approach with focus on retrofit measures that were most beneficial to the individual property. It is evident through the evaluation of this study that the correct installation of the retrofit measures can improve the thermal performance of the property, provide desired comfort to the occupants, drive down the cost of energy bills and in return the reduction of energy consumption. Insight into how cost reductions were driven in the project, and how further reductions in cost might be delivered in future, are not within the scope of this report but will be reported on separately by Innovate UK.

The evaluation of these homes has reflected the findings observed in the broader 'Scaling up Retrofit' project showing that the correct installation of retrofit measures can improve the thermal performance of a property allowing occupants to achieve desired comfort levels with reduced energy consumption, reflected in the cost of their energy bills.

2. Introduction

This report summarises the findings from a six-month monitoring evaluation study on four properties that were retrofitted with energy efficiency measures as part of Innovate UK's 'Scaling up Retrofit' project.

3. Background

PRP was the Lead Partner of a consortium that undertook the Scaling up Retrofit project, a research project that was funded by Innovate UK.

The project built on a number of residential retrofit desktop research studies by PRP, with the primary aim of demonstrating the viability of the technical, process and commercial models. The previously developed whole house retrofit solution was tested and refined through an iterative process of detailed technical development followed by demonstration trials on 10 properties that are of a similar typology.

The core objective was to prove our project hypothesis that through the iterative trial process, a two-bedroom or three-bedroom semi-detached house could undergo a full thermal retrofit for approximately £15,000 in less than 10 working days, achieving 25% to 40% reduction in heat energy consumption, with minimum disruption to the residents. The project aimed to achieve this by developing robust surveying, design and installation solutions which would improve the technical performance while maintaining the aesthetic quality of the building. The householders' needs for good value, trusted suppliers and minimal disruption were also key to this approach to delivering mass scale residential retrofit. The scheme will connect households with dependable local teams and the developed commercial model will be suitable for delivery by small local firms and large organisations, both working with quality assured, trusted suppliers.

The retrofit solution consisted of a number of energy efficiency measures, including:

- The installation of external wall insulation and cavity wall insulation where required, with particular focus on technical solutions that tackle thermal bridging issues and the development of the following technical solutions and enabling products:
  - Below damp proof course (DPC) level insulation
  - Insulated removable reveals for windows
  - Roof eaves insulation
  - Bespoke solution for insulating around energy meter boxes
  - Chimney sealing solution
- The installation of single heat recovery fans in the wet rooms
- Draught-proofing
- The introduction of thermostatic radiator valves (TRVs) to the heating systems in the unoccupied properties that were retrofitted as part of the project

The retrofit solution aimed to address thermal bridging by targeting an improved U-value of 0.20 W/m^2K for walls and 0.15 W/m^2K for roofs.

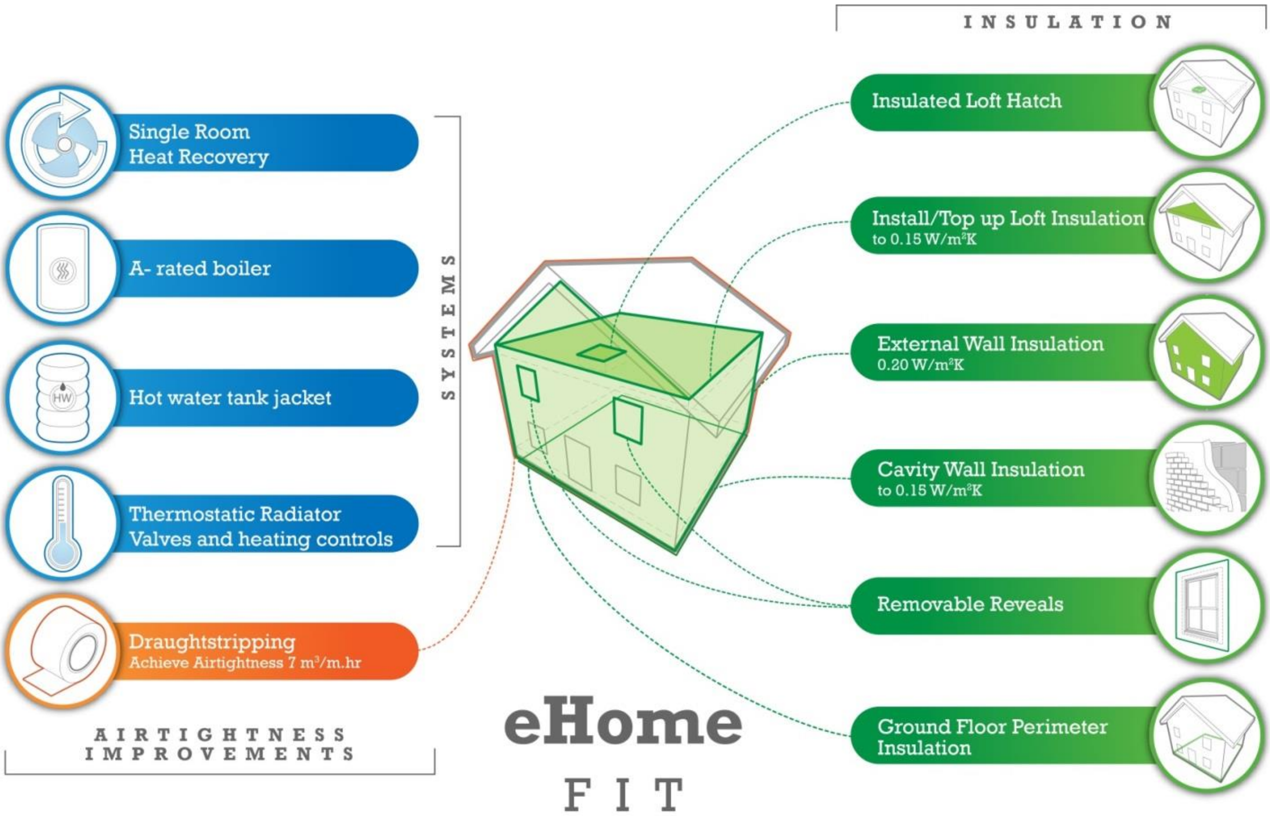


Figure 1: Infographic of the retrofit solution

The retrofit of the properties was undertaken as an iterative process through September 2014 to May 2016, with the learning from each of the iterations being fed into the subsequent retrofit works. There were a total of five iterations and a pair of semi-detached houses was selected to undergo the retrofit work each time. The first iteration was carried out in unoccupied properties while the remaining four were carried out in occupied homes. The cost of the retrofit was around £16,000 per property.

In-home environmental monitoring equipment was installed to capture environmental data, which allowed us to measure and analyse the energy performance before and after the retrofit works.

However, as the project lead for the post-retrofit data collection went into administration the project consortium was unable to complete this work. The Department for Business, Energy and Industrial Strategy (BEIS) has since provided the funding required to continue the environmental monitoring of the retrofitted homes and to carry out the post-retrofit surveys and analysis. The collected datasets allowed PRP to assess the energy and environmental benefits of the retrofit works.

4. Methodology

The aim of this study was to understand the impact of the energy efficiency measures on the properties. Four properties were selected to have monitoring equipment installed. Although it was a relatively small study sample, the data provides insights into the effectiveness of retrofit solutions through the evaluation of the following areas:

- Energy consumption savings
- Associated CO_2 savings
- Building performance
- Resident's perception of the internal comfort conditions and any related lifestyle changes

The evaluation was undertaken by answering the following four research questions:

RQ1: What are the energy savings and corresponding CO_2 savings for each house monitored?

RQ2: What are the costs per tonne of CO_2 reduction?

RQ3: How have internal temperature and relative humidity changed following the retrofit?

RQ4: What do the residents think of the retrofit and its impact on their home?

The evaluation was undertaken through a combination of quantitative and qualitative research methods; the collection of environmental and energy data from the four properties, the use of an air permeability test (at one property) and thermal imaging surveys (at all properties), and qualitative interviews with the residents.

4.1 Property Selection

One property from each of the four retrofit iterations involving occupied homes (second to fifth iterations) was selected for this study. As a reference point, they were referred to as D1, D3, D6 and D10.

D1, D3 and D6 were inter-war properties with solid wall construction, whereas D10 was built in the 1960s with cavity wall construction.

D1 was a three-bedroom semi-detached house with seven occupants (including five children). The total floor area of the property was 79m^2. D1 was one of the final homes to be retrofitted (fifth iteration) and the retrofit work was undertaken at this property in May 2016.

D3 was a three-bedroom semi-detached house with three occupants at the start of the project. One of the occupants moved out during the project and there were currently two occupants at the property. The total floor area of the property was 80m^2. D3 was retrofitted in the third iteration and the retrofit work was undertaken at this property between December 2014 and February 2015.

D6 was a two-bedroom semi-detached house with two adult occupants. The total floor area of this property was 57m^2. D6 was retrofitted in the second iteration and the retrofit work was undertaken at this property between September 2014 and November 2014.

D10 was a two-bedroom semi-detached house with four occupants (including two children). The total floor area of this property was 65m^2. D10 was retrofitted in the fourth iteration and the retrofit work was undertaken at this property between October 2015 and December 2015, however, the snagging period took a little longer than the other three properties.

Figure 2 shows the programme of the retrofit iterations.

Year	2014				2015												2016					
Month	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6
D1																					Iteration 5	
D3				Iteration 3																		
D6	Iteration 2																					
D10														Iteration 4								

Figure 2: Retrofit programme of the four selected properties

4.2 Data collection

Monitoring equipment was installed within the properties to collect environmental data, which included:

- Real time data loggers to record the temperature and relative humidity of the principal habitable rooms, i.e. the living room, the kitchen, the bathroom and the main bedroom.
- Real time data loggers to record the CO_2 levels in the living room and the main bedroom.
- Battery-powered data loggers to record the temperature of these principal habitable rooms.
- Battery-powered data loggers to record (as a back-up) to record the temperature and relative humidity of these principal habitable rooms, except in the kitchens where there was no radiator installed.
- External temperature data was extracted from the Weather Database using the weather station located locally in Dartford.

All data was recorded at 15-minute intervals.

Environmental data collected from the real time data loggers from 26/27 October 2016 to 24 March 2017 was used as the post-retrofit datasets for the evaluation of D1, D3 and D6. Environmental data collected from the battery-powered data loggers from 26/27 October 2016 to 15 March 2017 was used for the evaluation of D10.

Pre-retrofit datasets were obtained from the environmental data monitoring which formed part of the Scaling up Retrofit project:

- Real time data loggers to record the temperature and relative humidity of the principal habitable rooms within the properties, i.e. the living room, the kitchen, the bathroom and the main bedroom.
- Real time data loggers to record the CO_2 levels in the living room and the main bedroom.

Environmental data was collected between April 2014 and December 2015, and selective data was used for the evaluation. The selection was dependent on the availability of the data and the period when the retrofit works took place.

Utility bills were obtained from the utility companies in order to undertake assessment of the energy consumption data.

Data Analysis

4.3.1. Heating Degree Days (HDD) and Heating Degree Hours (HDH)

4.3

Heating Degree Days (HDD) and Heating Degree Hours (HDH) are tools to help understanding the correlation between the patterns of internal temperature and external temperature.

The use of HDD helps to understand the approximate heating requirement of a building, by measuring how much (in degrees) and for how long (in days) the air temperature was below a baseline temperature.

The baseline temperature of a building is assumed to be typically 15.5°C. When the temperature is below 15.5°C it is assumed that the building will require heating to maintain a comfortable internal temperature.

The HDD can be calculated using the following formula:

$$HDD = (\text{external temperature} - \text{baseline temperature } (15.5^{\circ}C)) \times 1 \text{ day}$$

Heating Degree Hours (HDH), used in this analysis, is a more granular expression of the HDD; the unit is per hour, rather than per day.

4.3.2. Energy Consumption Data Analysis

Data from the utility bills were used to calculate the carbon dioxide emissions for a period of 12 months, before and after the retrofit work was undertaken, where possible. The carbon dioxide emission figures were derived using the emission factor of 0.184 which was a typical value for domestic gas use.[1]

Calculations for the HDD data indicated that there was not a significant difference between the years and therefore annual gas consumption could be compared like-for-like.

Table 1: Heating degree days for years 2014 to 2016

Year	Total HDD
2014	1698
2015	1650
2016	1799

[1] Carbon dioxide factor (kgCO_2 / kWh) = 0.184 for domestic gas use
http://www.energysavingtrust.org.uk/about-us/our-calculations

4.4 Air permeability test and thermal imaging surveys

Specialist subcontractors were employed to undertake an air permeability test at one property (D1) and thermal imaging surveys at all four properties. Pre-retrofit test data was available as part of the Scaling up Retrofit project.

4.4.1. External thermal imaging surveys

External thermal images were taken of all four properties prior to and after retrofit measures were installed. These images showed the effectiveness of retrofit measures and highlight areas for improvement.

4.4.2. Internal thermal imaging surveys

Internal thermal imaging surveys were carried out at D3, D6 and D10. No internal thermal imaging survey was carried out at D1 due to occupant's request.

These internal thermal images highlighted any cold areas that might be caused by thermal bridging, i.e. areas in the building where there was a gap in the insulation. These areas of low thermal resistance would be colder than the surrounding areas and could be at greater risk of condensation. An aim of the retrofit work was to create a continuous and aligned layer of insulation that minimises the number of thermal bridges in the building. However, it is important to observe the thermal bridges in the properties that were retrofitted with insulation to better understand where retrofit had worked well and where it had been less effective.

Some of internal thermal images were analysed using the 'Thermal Index' method, which compared the internal surface temperature with the difference between internal and external temperatures to produce a weighted ratio of temperatures.

The Thermal Index is defined as $(T_{SI}-T_O)/(T_A-T_O)$ where:

T_{SI} = Average surface temperature of the Anomaly

T_O = Average External Temperature

T_A = Average Internal Temperature

Areas are more likely to be at risk of condensation when the Thermal Index (TI) is less than 0.75. This is most likely to occur in thermal bridges where the temperature of the anomaly area is much lower than the surrounding areas.

Moreover, internal thermal images were also effective at showing where retrofit installations had worked well.

4.5 Occupant interviews

Post-retrofit occupant interviews were undertaken in April 2017. The interview questionnaire was informed by the data analysis as part of this study and the format drawn from the pre-retrofit interviews. Pre-retrofit interviews were undertaken at the four properties as part of the Scaling up Retrofit project.

5. Findings from D1

5.1 Property details and occupancy patterns

D1was a three-bedroom semi-detached house, with a total floor area of 79m[2]. It was an inter-war property with solid wall construction, with a 1-storey extension at the rear of the property. The kitchen and the living room were located on the ground floor, the bathroom was located at the rear extension, and the bedrooms were located on the first floor. In terms of the orientation of the rooms, the kitchen faced southeast, the bathroom and the living room both faced southwest, and the main bedroom (the monitored bedroom) faced northeast.

The family living at D1 comprised seven people, including two adults and five children of various ages, from 4 to 21 years old. The husband worked full time and was usually on night shifts, whereas the wife stayed at home most of the time. The eldest son slept mostly at home during the day due to his night job. Two of the other children attended college and primary school respectively, and they were usually at home after school in the afternoon. The youngest children were twins and they shared the monitored bedroom with the parents. The family had got a small pet dog in February 2017.

5.2 Retrofit work undertaken

D1 was one of the final properties to be retrofitted (fifth iteration) and the retrofit work was undertaken at this property in May 2016.

Table 2: Some of the retrofit measures undertaken to tackle fabric heat loss

D1	Construction information	Retrofit measures
Walls	Solid wall, uninsulated	150mm wall insulation to the ground floor (25mm insulated brick slips finish) and 160mm to the first floor walls (render)
Roof	200 uneven insulation	None; only eaves insulation; insulation between rafters in the rear extension
Floor	Solid floor	None
Doors/windows	Double glazed; Less than 25 years old - very draughty and poorly installed	Insulated reveals where space allowed, draught-stripping all around

Table 2 shows the condition of D1 prior to retrofit and highlights some of the measures that were added to tackle fabric heat loss.

5.3 Thermal imaging survey results

Typical areas that were identified as regions of heat loss in D1 were bay window jambs, first floor windows and entrance door reveals, the junction between the ground floor roof and the main wall, below the DPC at the front and side walls and the trim between the ground and first floors. These areas were highlighted on the thermal images below to demonstrate whether retrofit was effective in reducing heat loss.

The full thermal imaging survey report can be found in Appendix A. Note: the following thermal images were labelled as the colour keys could be misleading if not carefully interpreted.

5.3.1. External thermal imaging - Walls

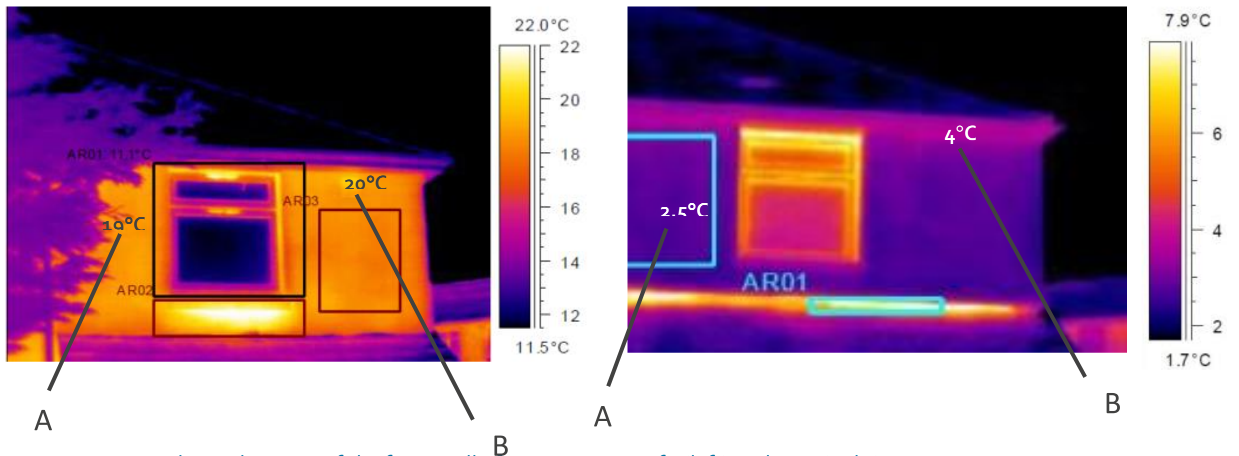


Figure 3: Thermal images of the front wall of D1 prior to retrofit (left) and post (right).

Figure 3 shows the exterior wall of D1, pre and post-retrofit. After 150mm of wall insulation was added to the first floor, the thermal performance was improved across the area. Specific areas highlighted a decrease in temperature loss; 16.5°C at point A and 16°C at point B, pre and post-retrofit. This equates to 87% and 80% of reduction in heat loss for points A and B respectively.

5.3.2. External thermal imaging - Doors

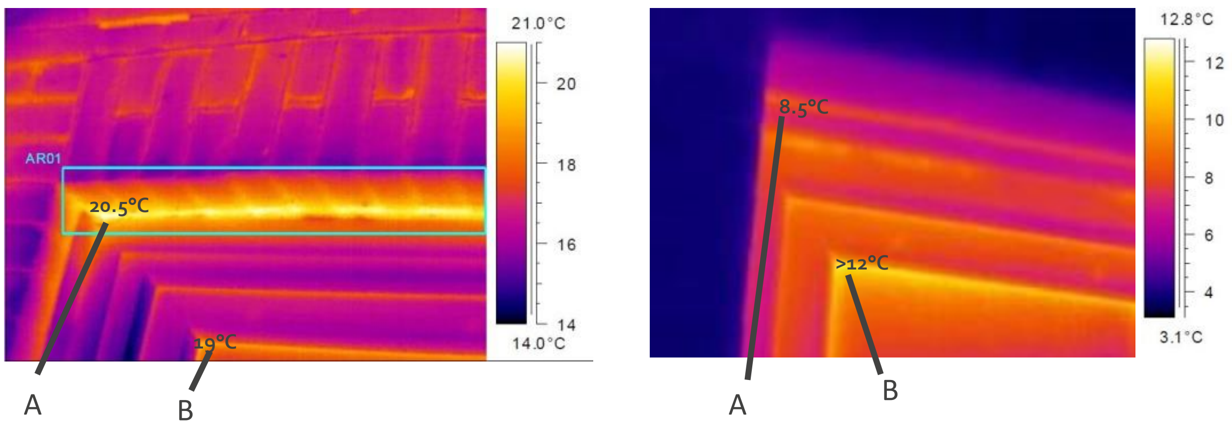


Figure 4: Thermal images of a door on D1 prior to retrofit (left) and post (right).

Figure 4 shows heat loss at the rear door of D1 that was insulated and draughtstripped as part of the project. A decrease in temperature loss was recorded, as shown in points A and B, with a difference of 12°Cand 12.5°C pre and post-retrofit respectively.

5.3.3. External thermal imaging - Below damp proof course (DPC) and trim between floors

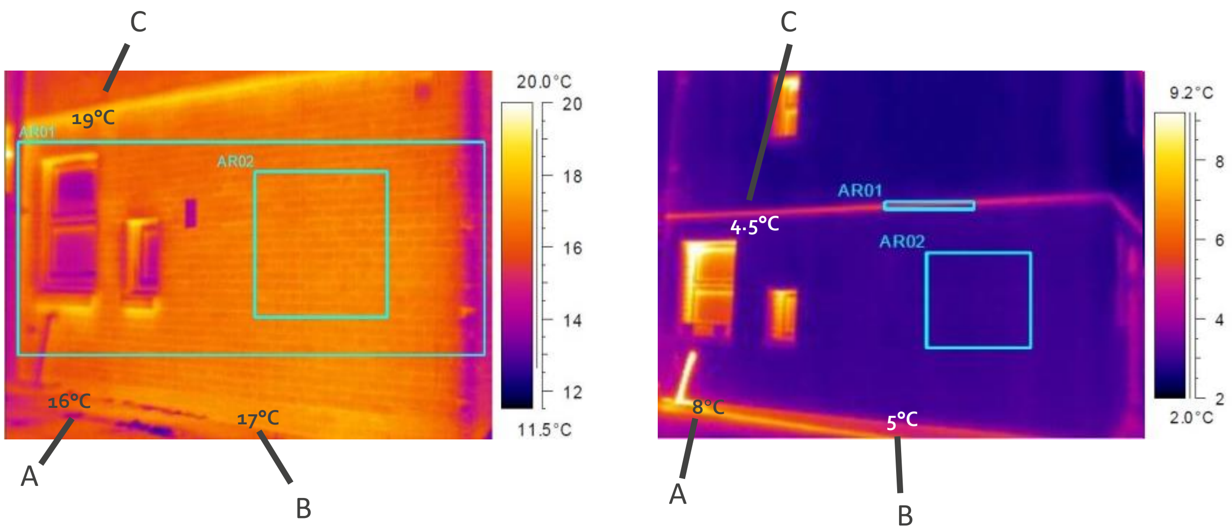


Figure 5: Thermal images the DPC on D1 prior to retrofit (left) and post (right).

Points A and B in Figure 5 both showed decreases in temperature loss around the below DPC area; 8°C and 12°C of difference pre and post-retrofit respectively. Point C showed the trim between the ground and first floor. Heat loss was reduced from 19°C to 4.5°C.

5.3.4. Internal thermal imaging

An internal thermal imaging survey was not undertaken at this property at the occupants' request.

5.4 Air permeability test results

An air permeability test was carried out at D1. The following table shows the test results pre and post-retrofit, for comparison. The full air permeability test report can be found in Appendix B.

The following were identified as air leakage points when tested before the retrofit work was undertaken:

- service penetration from the bathroom
- reveals (doors and windows)
- ceiling and skirting board junction with the party wall (cables penetration through ceiling)
- electric and gas meter surrounds

Post-retrofit test result showed that all of the above air loss routes were addressed and resolved, which meant that the property became more air-tight after the retrofit work was undertaken.

Table 3: Air permeability test result in D1

Air permeability test (pre-retrofit)	Air permeability test (post-retrofit)	Changes in air permeability due to retrofit (%)
8.62 $m^3.h^{-1}.m^{-2}$ @ 50 Pa	5.02 $m^3.h^{-1}.m^{-2}$ @ 50 Pa	-41.8%

5.4.1. In summary, there was a reduction of over 40% in air permeability due to the retrofit works. Environmental data analysis with occupant interview

The following section includes findings from the environmental analysis, coupled with information received from the occupant interview.

5.5

5.5.1. Selection of environmental data for analysis

Retrofit work was undertaken at D1 in May 2016 and therefore the following pre and post-retrofit datasets were selected for data analysis / comparison:

Table 4: period chosen for data analysis

	Monitoring Period
Pre-retrofit	Nov 2014 - Feb 2015
Post-retrofit	Nov 2016 - Feb 2017

5.5.2. Key findings

Results showed that the average room temperatures pre retrofit were usually around 20°C in the monitored bedroom, the bathroom and the living room, and around 22°C/23°C in the kitchen. Post retrofit temperatures were around 20°C/21°C in the monitored bedroom, and around 23°C/24°C in the bathroom, the living room and the kitchen (which were located on the ground floor) (see Table 5).

Table 5: Average internal temperatures in D1 pre- and post-retrofit

Period	Average room temperature in °C over the monitoring period				Average External Temperature over the monitoring period (°C)
	D1 Bedroom	D1 Bathroom	D1 Living Room	D1 Kitchen	
Nov 2014 – Feb 2015 (pre-retrofit)	19.5	20.3	20.4	22.5	6.3
Nov 2016 – Feb 2017 (post-retrofit)	20.5	22.7	23.5	23.7	5.8

There was a minimum of 1°C increase in the average room temperature post-retrofit and in the case of the living room the increase was almost 3°C. This was confirmed at the occupant interview there were different desired temperatures for each of the rooms. These temperature levels were controlled by the different settings of the respective TRVs that were set up when the occupants first moved in. These TRVs settings were not changed after the retrofit works were done. The monitored bedroom facing northeast was preferred to be slightly cooler, whereas the desired temperature of the bathroom was higher than the rest of the property. This was to make the young children's bath time in the evening more comfortable.

The occupant expressed that the property was much more comfortable post-retrofit, both in the colder and warmer months. The heating system at D1 was set on a timer, usually starting from 6am. Prior to the retrofit the heating system was left on during the day (and sometimes throughout the night) during the winter seasons, as the rooms seemed to become cold very quickly after the heating system was turned off. The occupant stated that since the retrofit work was undertaken, she felt that the house heated up more quickly and stayed warm for longer.

Since the completion of the retrofit work, the occupant would manually turn the heating off after it had been on for 1 to 1.5 hours, instead of keeping the heating on all day. She would occasionally override the settings to meet the household demands, depending on the weather and other activities, for example, work shifts and/or visits from friends and relatives. In particular, she stated that on a cold day, she would turn on the heating system for just a few minutes and it would already be sufficient to warm up the house to a comfortable temperature. She would sometimes turn the thermostat to the maximum temperature for up to half an hour and then leave it at 20°C for the rest of the day, which is the temperature that the thermostat was usually set for. The thermostat was previously set to 23°C pre-retrofit. It can therefore be deduced that the property is much warmer and is easier to warm up after the retrofit work was completed.

Comparison between pre and post retrofit data also indicated a slight reduction in the relative humidity levels in the rooms, as shown in Table 6. The occupant stated that the house used to be very damp before the retrofit work was undertaken, and there were signs of mould growth around the windows and doors reveals, and the bay window skirting. There was a constant feeling of damp in the house, particularly in the cupboards and under the stairs. The retrofit works has addressed the damp and condensation issues at the property, which had been one of the biggest concerns for the occupants over the years. The occupant was particularly happy that the damp and condensation issues had been tackled through the retrofit works.

Table 6: Average relative humidity in D1 pre and post-retrofit

Period	**Average relative humidity (RH) in % over the monitoring period**				**Average External RH over the period (%)**
	D1 Bedroom	**D1 Bathroom**	**D1 Living Room**	**D1 Kitchen**	
Nov 2014 – Feb 2015 (pre-retrofit)	73.5	68.7	65.5	60.7	90.1
Nov 2016 – Feb 2017 (post-retrofit)	69.9	59.8	55.8	55.9	90.8

Figure 6 and Figure 7 below show the frequency of the CO_2 levels (measured in parts per million (ppm)) in the living room and the bedroom post-retrofit. Although there was very limited data available, it appears that the air exchange was considered generally acceptable at the property, and was only occasionally over the ASHRAE recommendations of 1,000ppm.

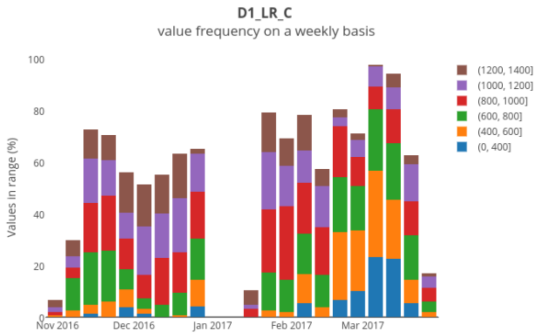


Figure 6: Frequency chart for CO_2 levels in D1's living room

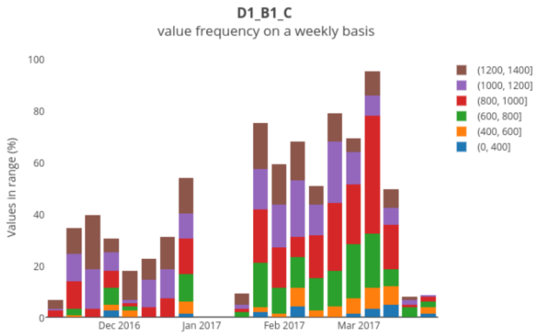


Figure 7: Frequency chart for CO_2 levels in D1's bedroom

More detailed observations of D1

5.6 Further analysis (Figure 8) showed that there were also smaller temperature variations in the monitored bedroom compared to the other three rooms. This is in line with our findings from the occupant interview that the monitored bedroom was preferred cooler.

The living room sometimes reached a maximum of 30°C, however, the occupant did not state that the temperature in the living room was uncomfortable.

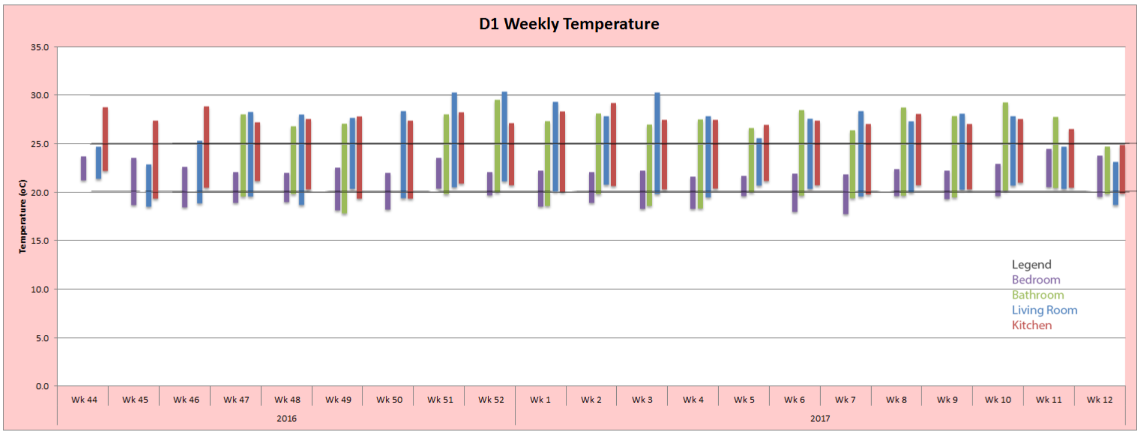


Figure 8: Average weekly internal temperatures in D1 post-retrofit

Data suggested that the radiator was turned on regularly in the bathroom while the radiator was not turned on at all in the bedroom and rarely in the living room. Figure 9 below shows a snapshot of the heating pattern for this property in February 2017. It is worth noting that the radiator temperature in the bathroom was a lot higher than the one in the living room, even though the average internal room temperatures in these rooms were quite similar. This suggested that the bathroom was heated constantly for various uses (including bathing the children and drying robes, as confirmed by the occupant), and that the radiator in the bathroom might have helped in heating the hall leading to the side door in the rear extension.

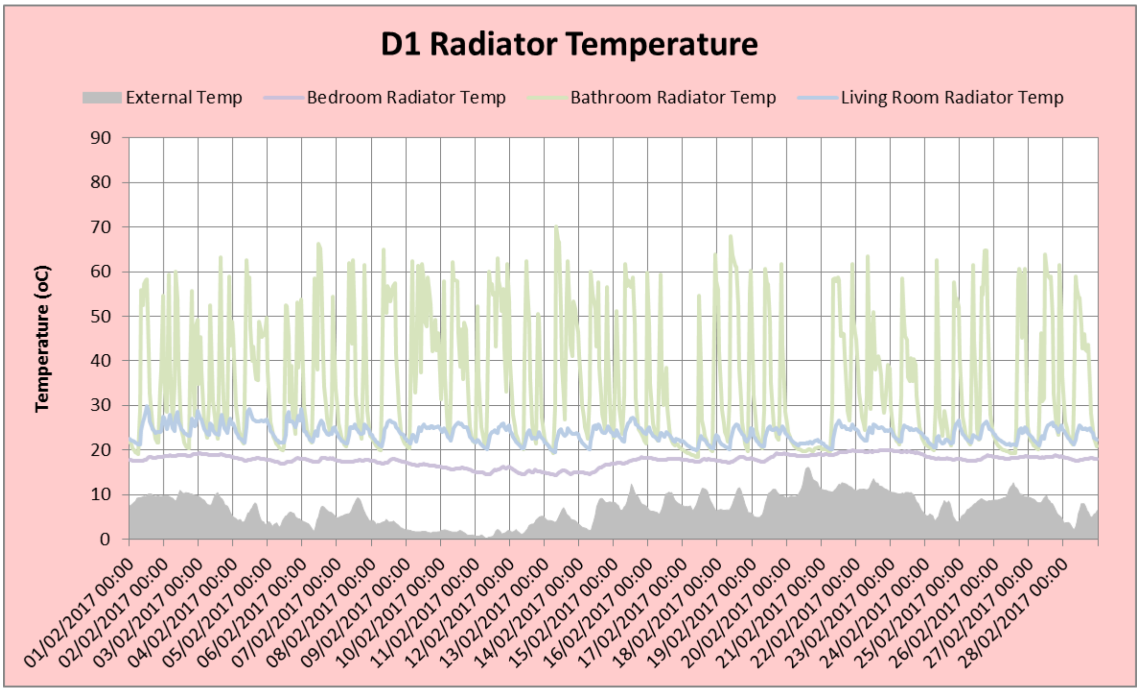


Figure 9: Average hourly radiator temperatures in D1 in February 2017 (post-retrofit)

The occupant confirmed that she did not feel that the air exchange generated by the heat recovery fan in the bathroom was sufficient (although it was functional) and therefore the rear windows facing the back garden had been sporadically opened to ventilate the room. Opening the windows also contributed to the heat loss in the bathroom and was another reason why the temperature of the radiator in the bathroom was high.

The occupant never opened the front windows before the retrofit work was undertaken because of the noises generated from the busy roundabout at the front of the house, which could be heard even when the windows are closed. As a result of draught-stripping (part of the retrofit measure), the draughts through the windows and the doors were eliminated (see the results of the air permeability test in the previous section). In addition, the noises from the front of the house were also reduced.

In general the occupant stated that the house was a much healthier environment to live in after the retrofit work was completed and that it had become a suitable place for their children to grow up in.

The occupant also thought that the house was more aesthetically pleasing and preferred the look of the house post-retrofit.

Energy consumption comparison

5.7

	Start of period	End of period	Gas Consumption (from actual readings)	Carbon dioxide emission (derived using emission factors)
Pre-retrofit	4/10/2014	29/3/2015	10,661 kWh	1,962 $kgCO_2$
Post-retrofit	3/10/2016	26/3/2017	9,299 kWh	1,711 $kgCO_2$
Difference			1,362 kWh	251 $kgCO_2$ (13% reduction)

The gas consumption was around 9,299kWh post-retrofit, which was below Ofgem's national average gas consumption figures of 12,000kWh[2]. The figures from pre and post-retrofit suggested that there could be a potential carbon dioxide savings of 13%.

Summary

5.8

D1 was one of the bigger properties that had retrofit works undertaken as part of the Scaling up Retrofit project. It was also one with the largest number of occupants. There were a number of small children and therefore the heating demand was higher than the other households of this study.

The retrofit works addressed the issues of mould growth and condensation, which was one of the key concerns of the occupants over the years. The average internal temperatures were increased post-retrofit which was confirmed by the occupants, who said that these temperatures were more comfortable and desirable. . There was a change of heating pattern post-retrofit and the occupant confirmed that the heating system was only required for a shorter period of time. However, only the thermostat was used to adjust the temperature at the property, TRV controls were not used by the occupants.

The gas consumption analysis indicated that approximately 13% of energy savings were achieved through the retrofit work, while the thermal images and the air test results suggested a reduction of over 40% in air permeability due to the retrofit works. The occupants were unable to heat the house to their desired temperature prior to the retrofit work and consequently there appeared to be a trade-off between comfort levels and energy consumption after the work was completed.

[2] https://www.ofgem.gov.uk/gas/retail-market/monitoring-data-and-statistics/typical-domestic-consumption-values

6. Findings from D3

Property details and household patterns

6.1 D3 was a three-bedroom semi-detached house with a total floor area of 80m². It was an inter-war property with solid wall construction. The kitchen and the living room were located on the ground floor, whereas the bathroom and the bedrooms were located on the first floor. In terms of the orientation of the rooms, the kitchen and the bathroom both faced east, whereas the living room and the main bedroom (the monitored bedroom) both faced west.

The occupants living at D3 included a woman in her 50s who spends most of her time at home due to her health conditions (the main occupant), and her son in his 20s who was in full time employment. Her daughter, who was a student, was living at D3 at the beginning of the Scaling up Retrofit project but left the house in 2016.

Retrofit work undertaken

6.2 D3 retrofit work was undertaken between December 2014 and February 2015, as part of the third iteration.

Table 7: Some of the retrofit measures undertaken to tackle fabric heat loss

D3	Construction information	Retrofit measures
Walls	Solid wall, uninsulated	150mm wall insulation (render finish)
Roof	200 uneven insulation	None
Floor	Partially suspended floor	None
Doors/windows	Double glazed; More than 25 years old - very draughty	Draught-stripping

Table 7 shows the condition of D3 prior to retrofit and highlights some of the measures that were added to tackle fabric heat loss.

6.3 Thermal imaging survey results

The typical areas identified as being vulnerable to heat loss in D3 in the thermal images below were: the junction between party walls and eaves, first floor windows head at junction with the eaves, below DPC at the junction with the external floor, the entrance door wall, the back door, the kitchen window and the soil pipe at the junction with the floor.

6.3.1. Walls

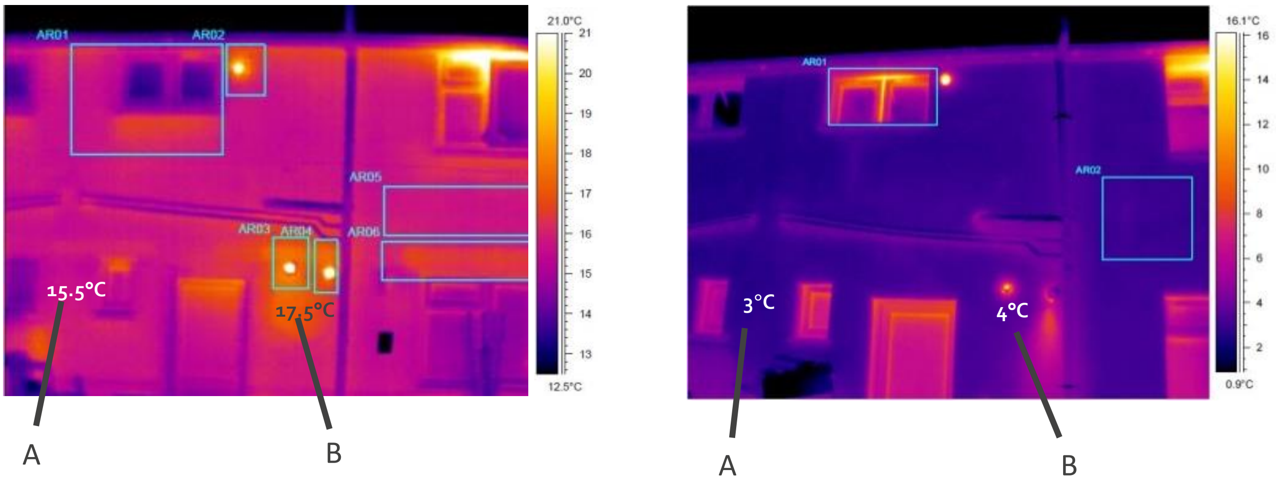


Figure 10: Thermal images of an external wall on D3 prior to retrofit (left) and post (right).

Figure 10 shows the thermal improvements post-retrofit on an external wall on D3 with 150mm of wall insulation added. The external surface of the wall was at a consistently lower temperature, which indicates that the retrofit worked well. Temperature losses decreased at point A from 15.5°C to 3°C and 17°C to 4°Cat point B; an average improvement of 13°C across the two points.

6.3.2. Roof

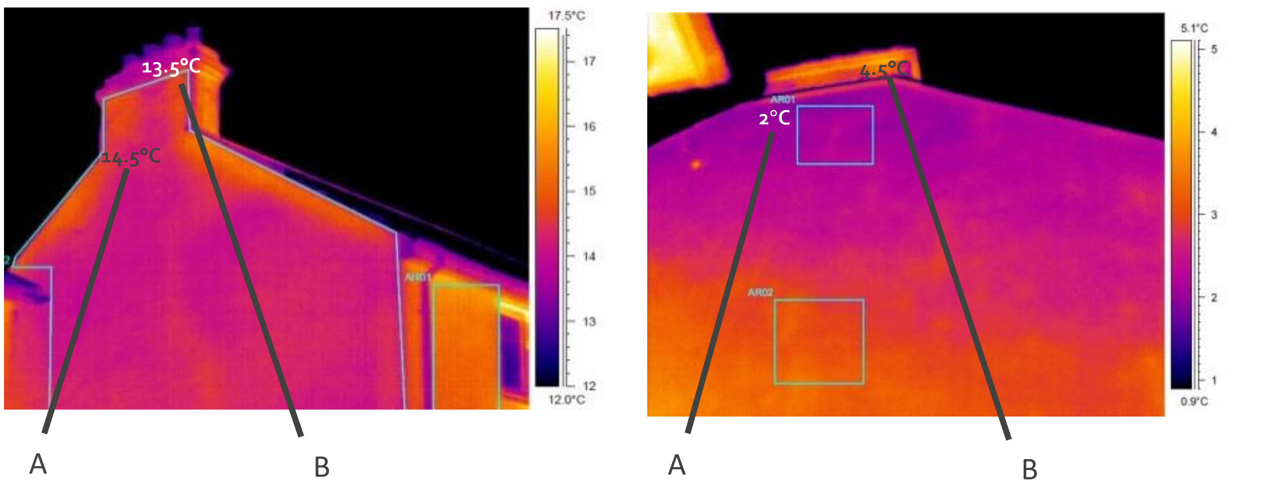


Figure 11: Thermal images of the roof on D3 prior to retrofit (left) and post (right).

The thermal image on the left of Figure 11 shows the roof on D3 prior to retrofit, with 200mm of uneven insulation, and post-retrofit (right), where the insulation was topped up to 320mm (making the cold roof wall 1.5ºC -2ºC colder than the rest of the façade). Again, points A and B were examples of the effectiveness of the retrofit measures. Point A, below the roofline, showed a 14.5°C heat loss and 2°C after the work; a 12.5°C of decrease in heat loss or an 86% of improvement. Point B showed 13.5°C of heat loss prior to the work and 4.5°C after. This equates to a 67% of decrease in heat loss.

6.3.3. Doors/Windows

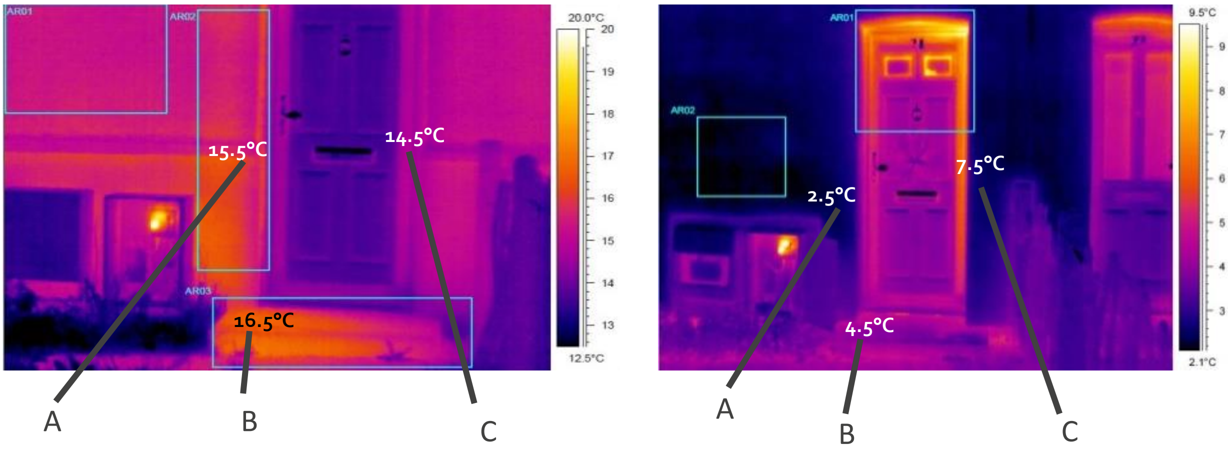


Figure 12: Thermal images of the front door on D3 prior to retrofit (left) and post (right).

Figure 12 shows the thermal improvements around the front door area of D3, which was draughtstripped. The area surrounding the door, points A and C, showed a decrease in heat loss; 2.5°C compared to 15.5°C for point A and 7.5°C compared to 14.5°C for point C. Point B showed the heat loss below the door which was reduced from 16.5°C to 4.5°C, this equates to a 73% decrease in heat loss after retrofit measures were installed.

6.3.4. Skirting

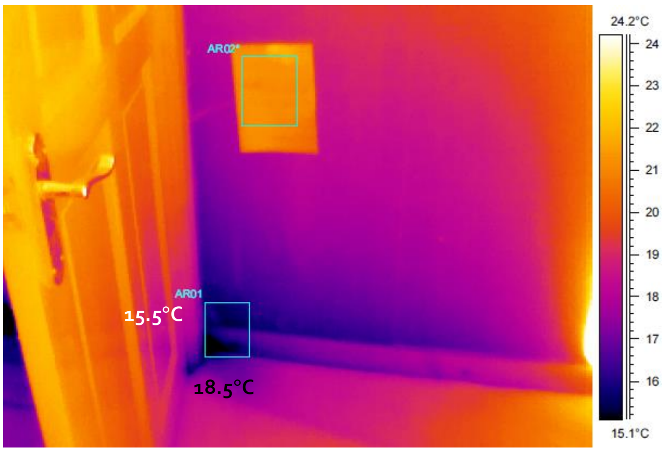


Figure 13: Thermal image of the entrance in D3.

Figure 13 shows an area of thermal bridging which posed a risk for damp developing. However, as there were meters on the other side of this wall the area was difficult to insulate. A temperature of 15.5°C and TI value of 0.45 in area AR01 also indicated that there was a slight risk of condensation and mould growth.

6.3.5. Ceiling

Figure 14: Thermal image of the back bedroom of D3

Figure 14 shows the back bedroom of D3; a TI value of 0.82 meant that the risk of condensation would be unlikely.

6.3.6. Doors

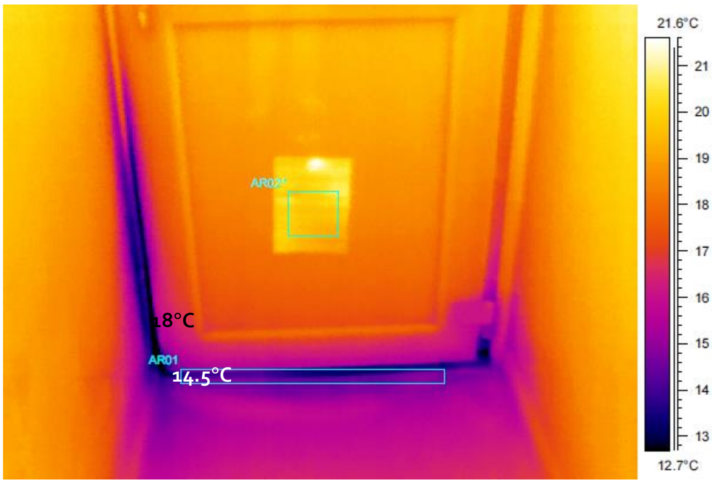


Figure 15: Thermal image of the wall door in the back hall of D3

Figure 15 shows areas that might be a risk of condensation around the door in the back hall of D3, because area AR01 was colder than the surroundings (14.5°C compared to 18°C). This indicated that a further draught-stripping could have been beneficial in this area.

6.4 Environmental data analysis with the occupant interview

The following section includes findings from the environmental analysis, coupled with information received from the occupant interview.

6.4.1. Selection of data for analysis

Retrofit work was undertaken between December 2014 and February 2015 and therefore the following pre and post-retrofit datasets were selected for data analysis / comparison. It should be noted that due to the problem with the data loggers at the start of the monitoring period, no data was collected between 26 October 2016 and 20 November 2016. Therefore, the data analysis was based on the data collected between December 2016 and February 2017.

Table 8: period chosen for data analysis

	Monitoring Period
Pre-retrofit	Oct 2014 - Nov 2014
Post-retrofit	Dec 2016 - Feb 2017

6.4.2. Key findings

Results showed that the average room temperatures pre-retrofit were usually around 20°C in the monitored bedroom and the kitchen, and around 22°C in the bathroom. No temperature data was available for the living room pre-retrofit. Post-retrofit temperatures were around 20°C in the monitored bedroom and the living room, and 22°C in the kitchen and the bathroom (see Table 9).

Table 9: Average internal temperatures in D3 pre and post-retrofit

Period	**Average room temperature in °C over the monitoring period**				**Average External Temperature over the monitoring period (°C)**
	D3 Bedroom	**D3 Bathroom**	**D1 Living Room**	**D1 Kitchen**	
Oct 2014 – Nov 2014 (pre-retrofit)	20.7	22.4	n/a	20.1	11.5
Dec 2016 – Feb 2017 (post-retrofit)	20.3	21.5	20.0	21.7	5.6

Our data analysis showed little temperature difference in the bedroom when comparing the pre and post-retrofit scenarios; the kitchen was warmer post-retrofit whereas the bathroom was cooler. However, it is worth noting that the external temperature was much lower in the post-retrofit data which suggested that more heating was required to keep the house warm.

However, the main occupant stated in the interview that prior to the retrofit works the heating system was not sufficient to keep the house warm, even when the heating system was turned on fully and running throughout the night.

The main occupant said that after the retrofit works was completed, the heating system was set on a timer and she would sometimes manually override the settings by turning the thermostat down when the temperature in the house was deemed to be too high.

All the TRVs in the property were set to the maximum and the occupants did not interact with them. Therefore the spare room that was used to be the daughter's bedroom was heated constantly even though it was not being used by anyone. The main occupant found that some of the rooms were warmer than others (in line with our data findings), but she was not sure how to adjust the TRVs and she tended to use the thermostat to regulate the desired temperature when she was in a particular room.

Because of her health conditions, the main occupant stayed at home for most of the time. Normally, she spent most of her time in the living room which was at the front of the house (west facing), despite it being the coldest room (in line with our data findings). She also stated that the kitchen (which had no radiator) was sometimes cold; however, it was usually warm enough when the cooking appliances were on. This contradicted with our data findings which indicated that on average the kitchen was the warmest room.

The main occupant required the house to be kept warm at all times. However, her son had sometimes found the house too warm and would often open all the windows to cool the house down when he returned in the evenings, especially in the living room and the kitchen. He would do this even in the coldest months of the year.

A comparison between the pre and post-retrofit data also indicated a reduction in the relative humidity levels in the rooms. Results showed that the average relative humidity levels were typically between 40% and 45% post-retrofit.

The main occupant sometimes experienced dryness in her mouth as she got up in the morning; this was reflected in the low relative humidity data gathered post-retrofit, which was quite low in the house.

There used to be draughts through doors and windows, which were substantially improved by the sealing works. Another area of improvement was the alleviation of condensation in the bathroom by the retrofit work.

Table 10: Average relative humidity in D3 pre and post-retrofit

Period	**Average relative humidity (RH) in % over the period**				**Average External RH over the period (%)**
	D3 Bedroom	**D3 Bathroom**	**D3 Living Room**	**D3 Kitchen**	
Oct 2014 – Nov 2014 (pre-retrofit)	66.5	55.5	n/a	69.9	90.7
Dec 2016 – Feb 2017 (post-retrofit)	41.8	42.7	41.6	42.7	92.2

The main occupant agreed that some of her heating and ventilation habits could be changed to adapt to the retrofitted home. For example, she would leave the heating on even when she felt warm, and would open the windows to cool down the room rather than turning the heating down. Another example was that she would open the windows to ventilate after using the shower or cooking. The main occupant confirmed that the window opening behaviour was more of a habit than a requirement because she felt that the heat recovery fan was effective enough to provide the air change needed.

The graphs below show the frequency of the CO_2 levels in the living room and the bedroom post-retrofit. The CO_2 levels in the living room and the bedroom were both below the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) recommendation threshold of 1,000ppm, which suggested good air exchange in these rooms. The results also showed that the bedroom was less well-ventilated than the living room, in line with the information gathered in the interview.

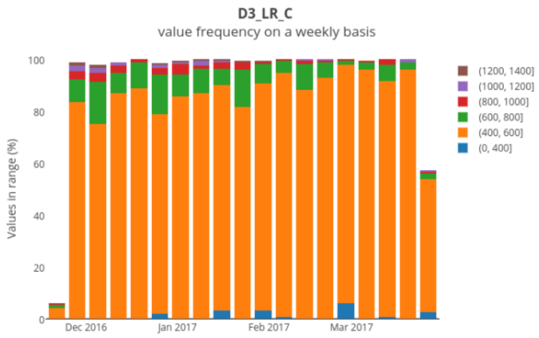


Figure 16: Frequency chart for CO_2 levels in D3's living room

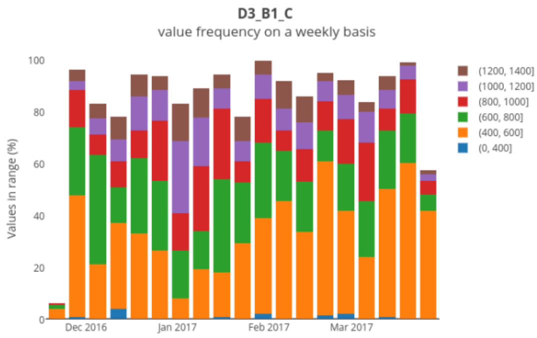


Figure 17: Frequency chart for CO_2 levels in D3's bedroom

6.4.3. More detailed observations of D3

The graphs below show that the average monthly relative humidity levels were mostly between 40% and 50%.

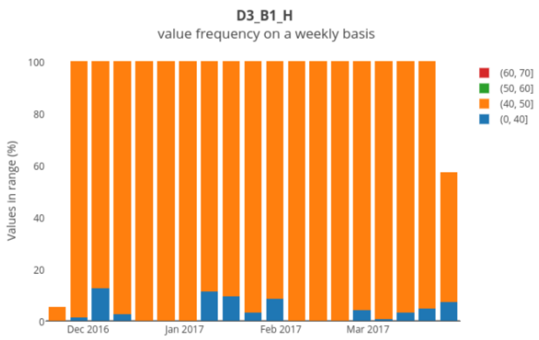


Figure 18: Frequency chart for RH in D3's bedroom

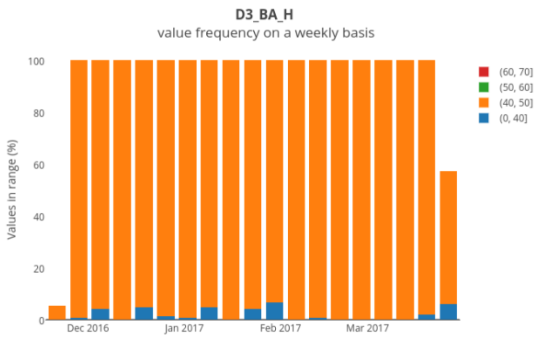


Figure 19: Frequency chart for RH in D3's bathroom

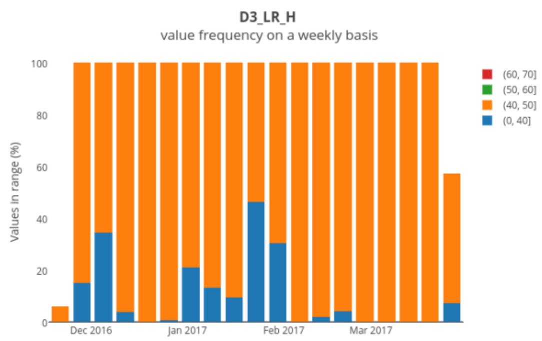


Figure 20: Frequency chart for RH in D3's living room

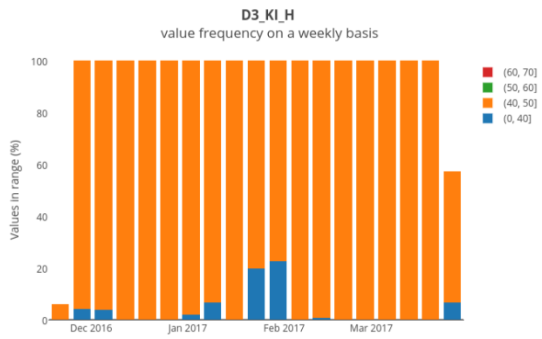


Figure 21: Frequency chart for RH in D3's kitchen

Data from one week in the pre-retrofit period and one week in the post-retrofit period was selected for closer inspection, taking into account the similarity between the external weather conditions (similar average external temperature and RH, and similar estimated HDH for the week), as shown below. Data showed that the average relative humidity levels in the rooms were lower and more regulated post-retrofit.

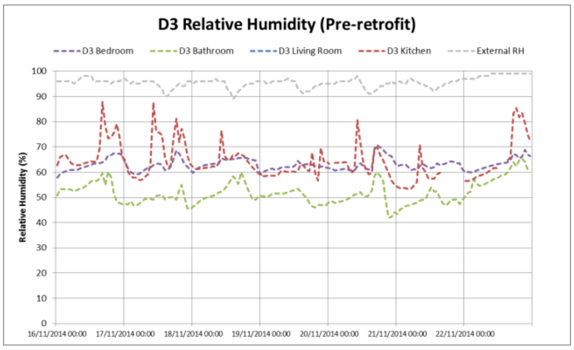


Figure 22: Average RH in D3 for a week pre-retrofit

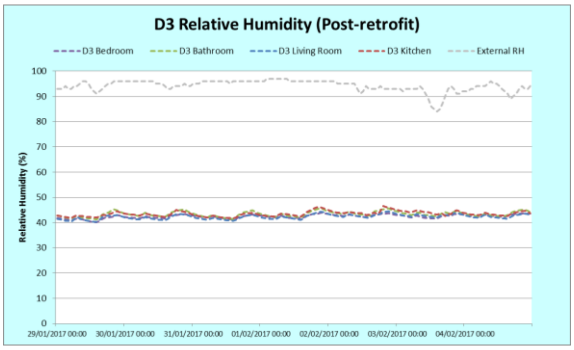


Figure 23: Average RH in D3 for a week post-retrofit

The graph below suggested that the radiator was turned on regularly in all the rooms, and that the heating system was programmed to be turned on at certain times of the day. This was confirmed by the occupant who said that the heating system was set on a timer during the winter period to be turned on at 6:30am for an hour and then again between 2:30pm and 9:30pm.

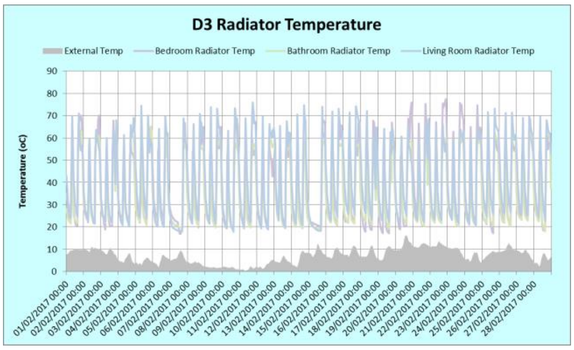


Figure 24: Average radiator temperatures in D3 in Feb 2017

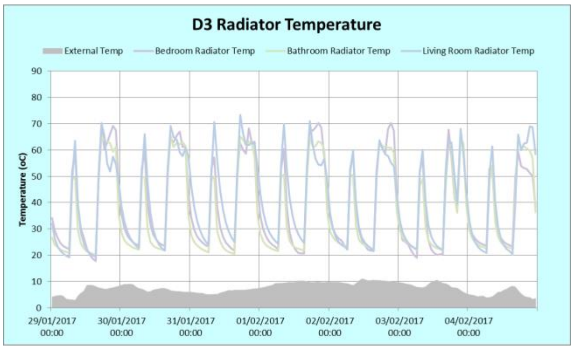


Figure 25: Average radiator temperatures in D3 for a week

Moreover, the occupant seemed to be happy with the change of appearance of the property, except a short period during the retrofit works when the property was coated with an experimental thick render base. She stated at the interview that she was now much happier, as the house was generally warmer, which was very desirable considering her specific needs.

6.5 Energy consumption comparison

	Start of period	End of period	Gas Consumption (from actual readings)	Carbon dioxide emission (derived using emission factors)
Pre-retrofit	11/4/2013	11/4/2014	15,421 kWh	2837 $kgCO_2$
Post-retrofit	19/1/2016	11/1/2017	10,410 kWh	1915 $kgCO_2$
Difference			5011 kWh	922 $kgCO_2$ (32% reduction)

The gas consumption was around 10,000kWh post-retrofit, which is just below Ofgem's national average gas consumption figures of 12,000kWh. The figures from pre and post-retrofit suggested that there could be potential carbon dioxide savings of 32%.

The occupant stated at the interview that prior to the retrofit works the heating system was not sufficient to keep the house warm, even when the heating system was turned on fully throughout the night. The gas bills were around £35 or £40 per week before the retrofit works took place. This had now significantly improved post-retrofit and the occupant found the house more comfortable without having the heating on at all times, and was spending no more than £25 per week in gas bills during the winter period. This was at least 25% savings in costs when compared to the gas bills pre-retrofit.

6.6 Summary

D3 was one of the bigger properties that had retrofit works undertaken as part of Scaling up Retrofit. One of the occupants had health conditions that required specific needs, resulting in higher heating demand.

The retrofit work tackled some of the issues of mould growth and condensation but thermal images suggested that there were areas that could benefit more by additional draught-stripping.

The main occupant agreed that some of her heating and ventilation habits could be changed to adapt to the retrofitted home. The environmental data analysis did not indicate a change of internal room temperature post-retrofit; however, it is worth noting that the external temperatures were lower post-retrofit which could mean that more heating was required to keep the house warm. Less gas consumption was found post-retrofit which confirmed that less energy was required to maintain the desired temperature of the house.

The main occupant said that after the retrofit works was completed, the heating system was set on a timer and she would sometimes manually override the settings by turning the thermostat down when the temperature in the house was deemed to be too high. TRV controls were not used by the occupants and all TRVs were set to a maximum which meant that when the heating was on, rooms that were not used (such as the unoccupied spare bedroom) were being heated in the same way.

The gas consumption analysis indicated that approximately 32% of energy savings was achieved through the retrofit work. However, it was clear from the interviews that there were other opportunities to further reduce the energy consumption, e.g. using the TRVs settings, changing window opening habits.

7. Findings from D6

Property details and household patterns

7.1 D6 was a two-bedroom semi-detached house with a total floor area of 57m^2. It was an inter-war property with solid wall construction. The kitchen, the living room and the bathroom were located on the ground floor, and the bedrooms were located on the first floor. In terms of the orientation of the rooms, the kitchen and the bathroom both faced northwest, and the living room and the main bedroom (the monitored bedroom) both faced southeast.

The property D6 was occupied by a couple in their 50s/60s. They both worked full time and, when at home in the evenings, they spent most of the time in the southeast-facing living room, next to the main road. The couple would keep the doors shut in the colder months to keep the room warm, and would leave the bathroom door open at all times to allow the heat to be transferred into the kitchen, which had no radiator and was more likely to be cold.

Retrofit work undertaken

7.2 D6 was retrofitted in the second iteration and the retrofit work was undertaken at this property between September 2014 and November 2014.

Table 11: Some of the retrofit measures undertaken to tackle fabric heat loss

D6	Construction details	Retrofit measures
Walls	Solid wall, uninsulated	140mm wall insulation (render finish)
Roof	100mm uneven insulation	Topped up to 320mm
Floor	Solid floor	None
Doors/windows	Double glazed; Less than 25 years old - very draughty	Insulated removable reveals installation, draught-stripping
Eaves	Sloped uninsulated eaves	External and internal insulation

Table 11 shows the condition of D6 prior to retrofit and highlights some of the measures that were added to tackle fabric heat loss.

7.3 Thermal imaging survey results

The typical areas that were identified as vulnerable to heat loss in property D6 and shown in the pre-retrofit thermal images below were: eaves (right hand side of the property only), the entrance door wall, kitchen window reveal and the trim between windows.

7.3.1. Walls

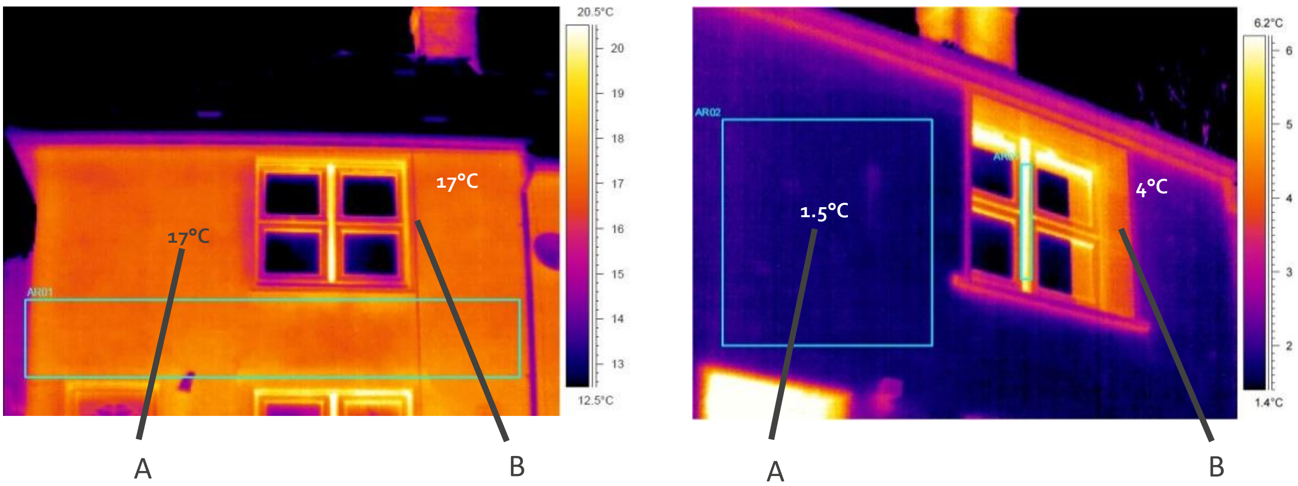
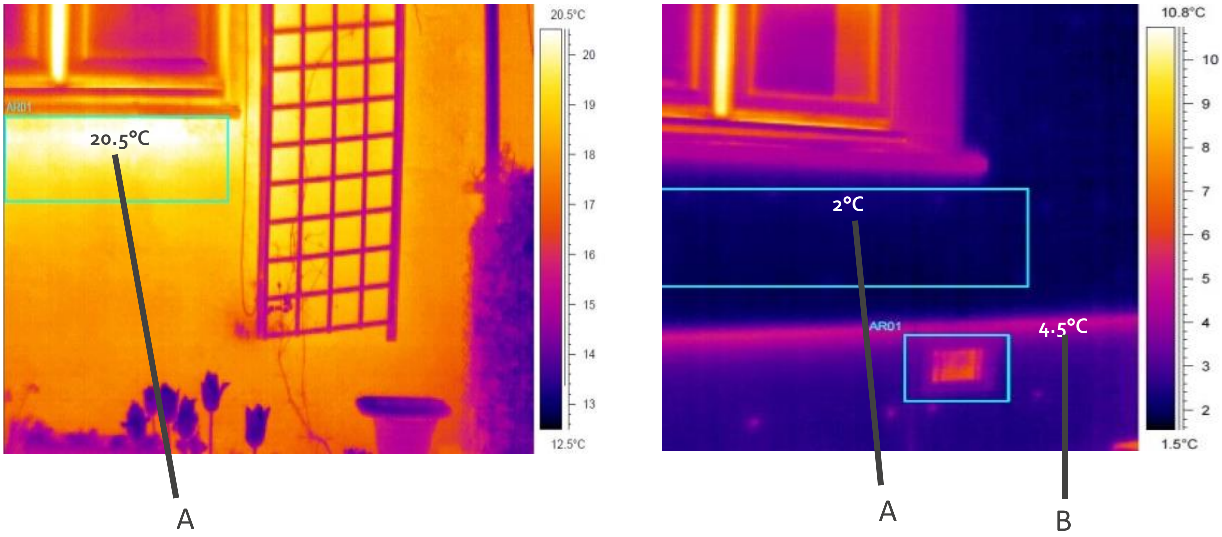


Figure 26: Thermal images of a window and eaves on D6 prior to retrofit (left) and post (right).

Figure 26 shows how solid wall insulation had improved the thermal performance of the building on the external front wall. The window reveals were warmer than the average temperature recorded on the walls (from 17°C to 1.5°C, point A) as shown in the right hand side picture, which was expected due to the thickness of the insulation installed in this area, however, the temperature decreased considerably as opposed to the pre-retrofit scenario, where temperature had decreased from 17°C to 4°C (point B).



7.3.2. Windows and Below DPC

Figure 27: Thermal images of a window on property D6 prior to retrofit (left) and post (right)

Figure 27 shows the window and below DPC area of property D6 prior to and after the works. Point A highlighted that retrofit had been effective in reducing heat loss from the space around the window sill; temperature loss had been reduced from 20.5°C to 2°C. Point B shows the area below DPC post-retrofit; heat loss was low at 4.5°C.

7.3.3. Eaves

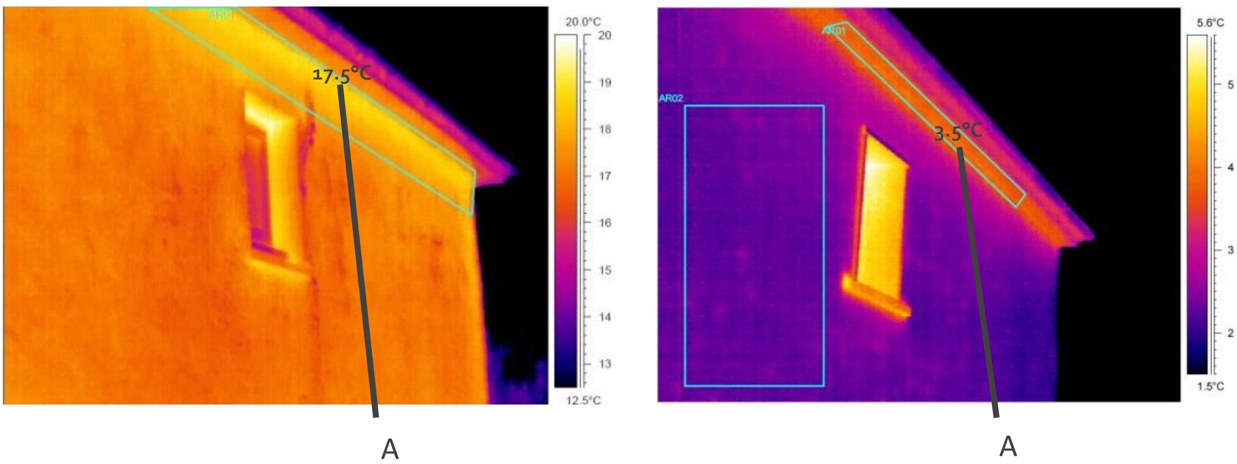


Figure 28: Thermal images of a window on property D6 prior to retrofit (left) and post (right)

Figure 28 shows the eaves on property D6 before and after retrofit installations. External and internal insulation had reduced heat losses; point A shows 17.5°C of heat loss on the pre-retrofit building and 3.5°C after it has had the retrofit work undertaken.

7.3.4. Skirting

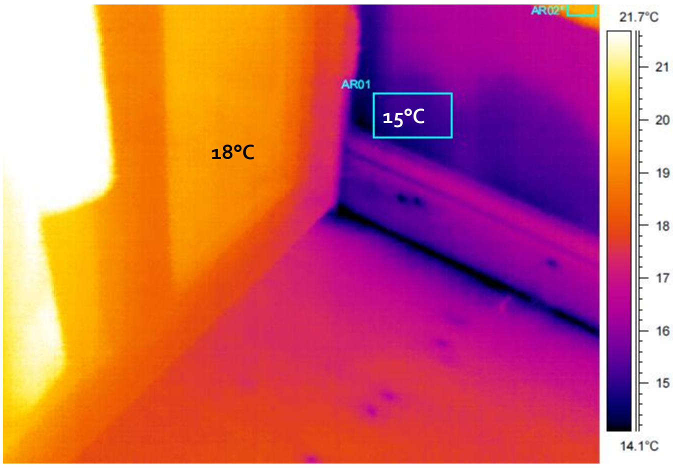


Figure 29: Thermal image of the living room skirting in property D6 post-retrofit.

Figure 29, taken in the living room corner, shows air leakage above the skirting, where it met the floor and wall. The temperature of this area, 15°C, was colder than its surroundings. Furthermore, a TI value of 0.62 in area AR01, caused by the low surface temperature compared to the internal temperature, indicated that there was a slight risk of damp and mould growth.

7.3.5. Windows

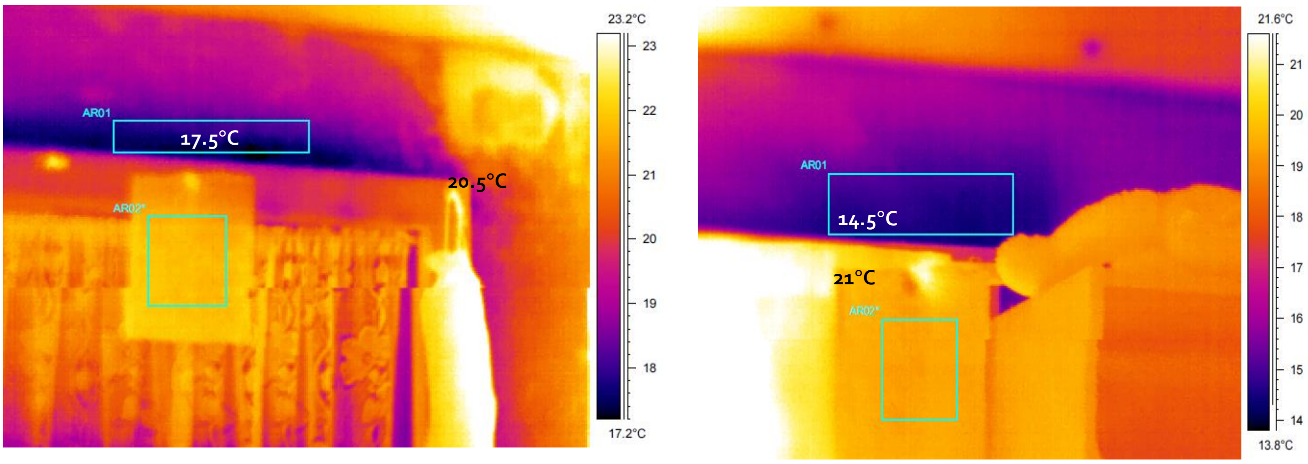


Figure 30: Thermal images of window areas in the kitchen (left) and bedroom (right) in property D6.

Figure 30 shows the lower temperatures above a window in the kitchen and back bedroom that could indicate areas of thermal bridging. Temperatures of 17.5°C and 14.5°C in area AR01 compared to 20.5°C and 21°C in the surrounding area meant that there was a potential risk of condensation (TI values of 0.72 and 0.61 for the area in AR01). Further draught-stripping in this area could be needed.

Despite weaknesses in some of the retrofit work and evidence of thermal bridging there were many areas where retrofit had been effective in reducing heat loss.

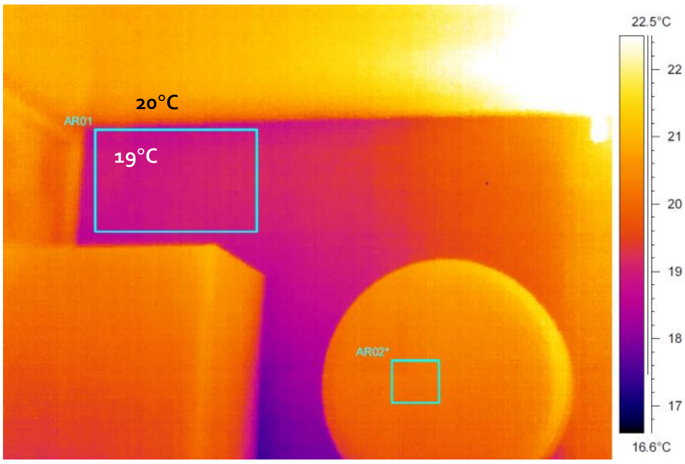


Figure 31: Thermal image of kitchen wall in property D6 with a TI value of 0.90

Figure 31 shows an area where retrofit measures had been successful in reducing thermal bridging, resulting in a TI value of 0.90. Temperatures between the wall and the ceiling were similar, again showing that the measures had reduced heat loss consistently and that the area was unlikely to become damp.

7.4 Environmental data analysis with the occupant interview

The following section includes findings from the environmental analysis, coupled with feedback received from the occupant interview.

7.4.1. Selection of data for analysis

Retrofit work was undertaken between September 2014 and November 2014 and therefore the following pre and post-retrofit datasets were selected for data analysis / comparison:

Table 12: period chosen for data analysis

	Monitoring Period
Pre-retrofit	May 2014
Post-retrofit	Nov 2016 - Feb 2017

7.4.2. Key findings

Results showed that the average room temperatures pre-retrofit were usually around 20°C in all the rooms. Post-retrofit temperatures remained at similar levels, with a drop of temperature in the monitored bedroom to around 17°C (see Table 13).

Table 13: Average internal temperatures in D6 pre and post-retrofit

Period	Average room temperature in °C over the monitoring period				Average External Temperature over the monitoring period (°C)
	D6 Bedroom	D6 Bathroom	D6 Living Room	D6 Kitchen	
May 2014 (pre-retrofit)	19.7	19.8	20.4	20.6	14.5
Nov 2016 - Feb 2017 (post-retrofit)	17.1	18.5	19.0	19.3	5.8

Our data analysis showed little temperature difference between the pre and post-retrofit scenarios; however it is worth noting that the external temperature was much lower post-retrofit which suggested that more heating may be required to keep the house warm.

The occupants had always controlled the heating system manually; the heating system was never set on a timer and the occupants would turn it on only when required. After the retrofit works were carried out the occupants would usually turn the heating system on for an hour before bedtime, which they felt was sufficient to provide a comfortable environment for them, even on colder days.

The occupants felt that the rooms needed to be heated to different temperatures and had initially set the TRVs to the desired settings when they moved in; however, they had not interacted with them since. The radiator in the monitored bedroom had always been turned off and the occupants would sometimes use an electric blanket to keep themselves warm during very cold nights.

Comparison between pre and post-retrofit data also indicated a reduction in the relative humidity levels in the rooms. The occupants stated that the house used to be very humid before the retrofit work was undertaken. The condensation issues that occurred previously in the bathroom had been addressed through the retrofit works. The issue of mould on the window's lintel in the spare bedroom (facing northwest) was also tackled with the retrofit work.

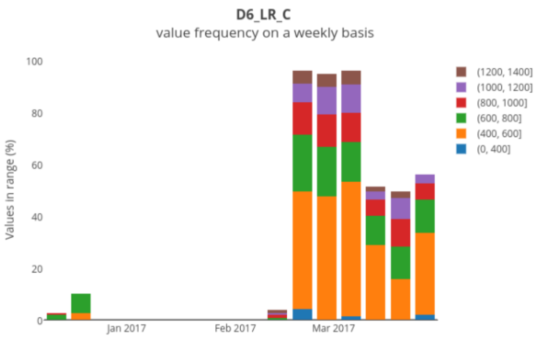
The occupants would still keep the windows open while using the shower or cooking. They had turned off the heat recovery fans that were installed in the wet rooms because they did not like the noises these heat recovery fans were making.

Draughts had been diminished substantially since the retrofit work, although the occupant stated that some were still present at the back door and windows in the kitchen (facing northeast), this was particularly evident in the colder months.

Table 14: Average relative humidity in D6 pre and post-retrofit

Period	Average relative humidity (RH) in % over the monitoring period				Average External RH over the monitoring period (%)
	D6 Bedroom	D6 Bathroom	D6 Living Room	D6 Kitchen	
May 2014 (pre-retrofit)	67.9	72.8	68.1	66.7	77.7
Nov 2016 - Feb 2017 (post-retrofit)	39.5	40.5	40.9	41.1	90.8

The graphs below shows the frequency of the CO_2 levels in the living room and the bedroom post-retrofit. Although there was very limited data available, it appears that the air exchange was considered generally acceptable at the property, and would only occasionally go over the ASHRAE recommendations of 1,000ppm.



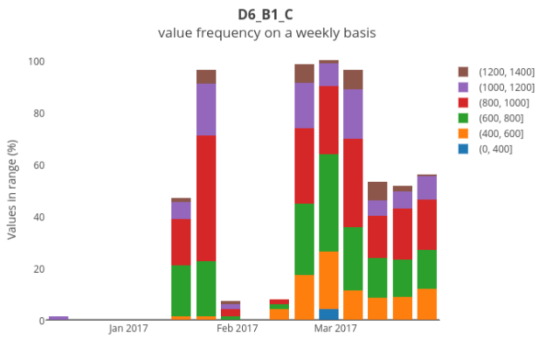


Figure 32: Frequency chart for CO_2 levels in D6's living room

Figure 33: Frequency chart for CO_2 levels in D6's bedroom

7.4.3. More detailed observations of D6

Results showed that the average relative humidity levels were typically around 40% during the monitoring period. The below graphs show the frequency of the relative humidity levels from a number of data ranges and suggests that the humidity levels did not exceed 50% during the monitoring period.

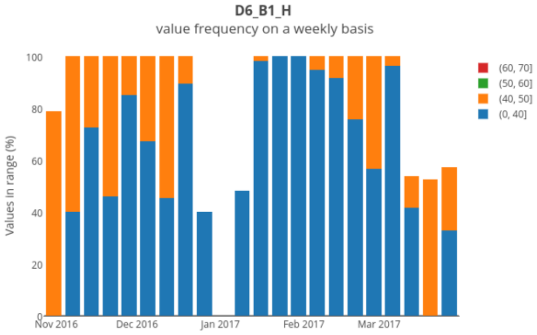


Figure 34: Frequency chart for RH in D6's bedroom

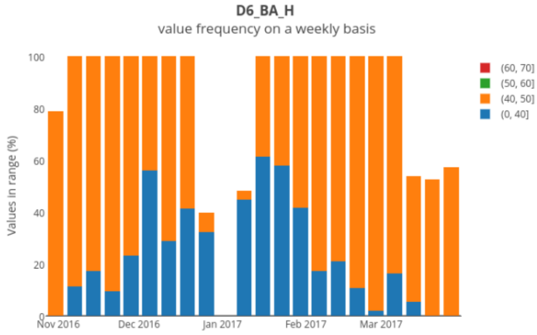


Figure 35: Frequency chart for RH in D6's bathroom

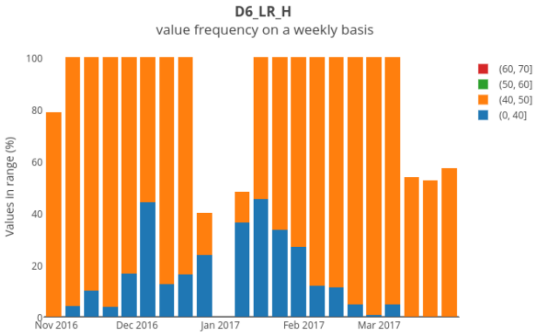


Figure 36: Frequency chart for RH in D6's living room

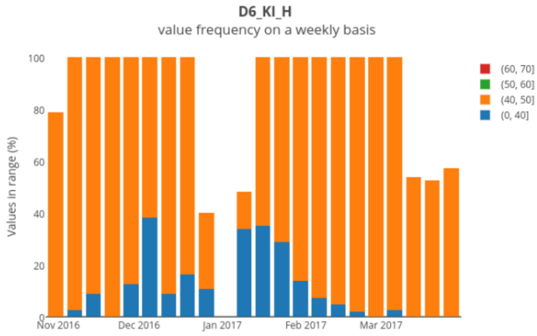


Figure 37: Frequency chart for RH in D6's kitchen

Data from one week from the pre-retrofit period and one week from the post-retrofit period was selected for closer inspection. For D6, as there was not much data in the winter period pre-retrofit (the retrofit work started in September 2014), a week in May 2014 was selected to compare with a week in March 2017, as shown below. Data showed that the average relative humidity levels in the rooms were more effectively regulated and lower in the post-retrofit scenario.

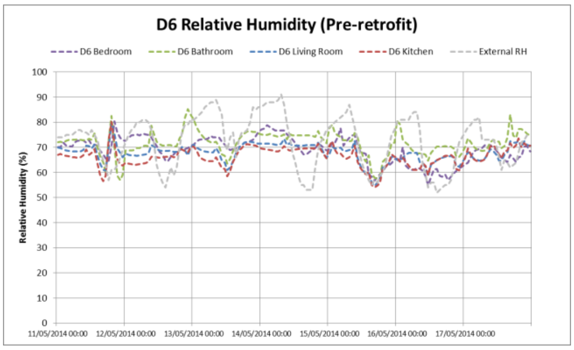


Figure 38: Average RH in 63 for a week pre-retrofit

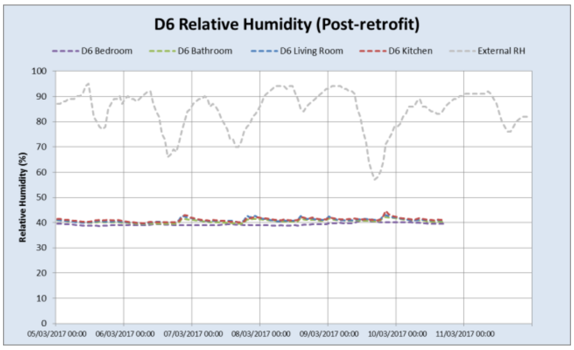


Figure 39: Average RH in D6 for a week post-retrofit

The graphs below suggest that the radiator was turned on regularly in the bathroom and in the living room, while the radiator was not turned on at all in the bedroom. This is in line with the information provided by the occupant at the interview.

On closer investigation (by looking at the temperature on a chosen week, i.e., week 10, in March 2017), it was confirmed that the heating system usage pattern matched the occupant's description in the interview.

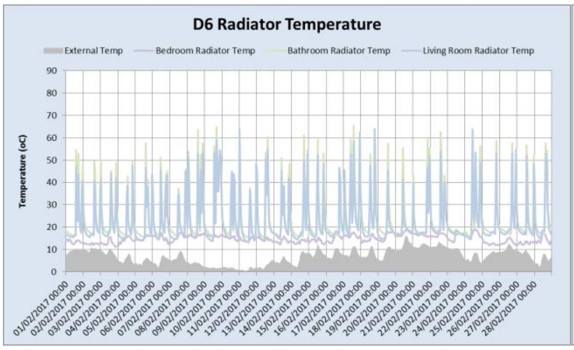


Figure 40: Average radiator temperatures in D6 in Feb 2017

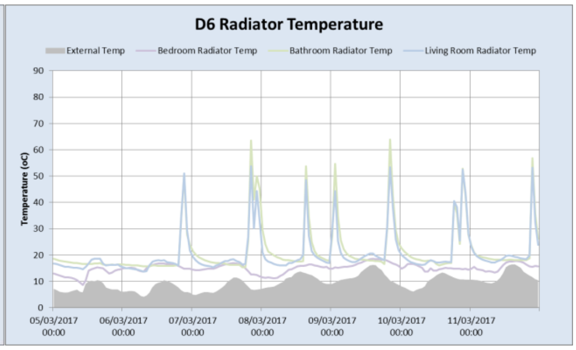


Figure 41: Average radiator temperatures in D6 for a week

7.5 Energy consumption comparison

	Start of period	End of period	Gas Consumption (from actual readings)	Carbon dioxide emission (derived using emission factors)
Pre-retrofit	05/10/2013	06/10/2014	4,832 kWh	889 $kgCO_2$
Post-retrofit	07/10/2015	06/10/2016	4,561 kWh	839 $kgCO_2$
Difference		Difference	271 kWh	50 $kgCO_2$ (5% reduction)

The gas consumption was around 4,500kWh post-retrofit, which was well below Ofgem's national average gas consumption figures of 12,000kWh. The figures from pre and post retrofit suggested that there was no significant difference in terms of gas consumption; this is likely to be because of the already very low gas usage at D6, confirmed by the occupants.

7.6 Summary

D6 was one of the smaller properties that had retrofit works undertaken as part of the Scaling up Retrofit. Both occupants were in full time employment and were only at home during the evenings and some of the weekends, therefore D6 had a lower heating demand compared to the other three properties in this study.

The retrofit works had regulated the relative humidity levels of the property and reduced the risk of condensation and mould growth. There was no significant difference in terms of the average internal temperature pre and post-retrofit and it was confirmed at the interview that the occupants preferred the house to be slightly cooler and they would only turn the heating on an hour before bed to make it comfortable to sleep in.

The gas consumption analysis indicated that only approximately 5% of energy savings was achieved through the retrofit work, which was low compared to the other properties. However, it was clear that the occupants at D6 were not heavy energy users even before the retrofit took place.

8. Findings from D10

8.1 Property details and household patterns

D10 was a two-bedroom semi-detached house with a total floor area of 65m². It was built in the 1960s with cavity wall construction. The property had a rear extension, however, only the inner wall of the rear extension was retrofitted as the space was not inhabited by anyone and was only used for storage. The kitchen and the living room were located on the ground floor, and the bathroom and the bedrooms were located on the first floor. In terms of the orientation of the rooms, the kitchen, the bathroom and the master bedroom (the monitored bedroom) faced southeast, whereas the living room faced northwest.

The family living at D10 comprised four people, including two adults and two children who were under 12 years old. The mother was in her 30s and had been in part time employment since the beginning of the Scaling up Retrofit project, whereas the father, who was away in the first two years of the project, had been at home for most of the time.

8.2 Retrofit work undertaken

D10 was retrofitted in the fourth iteration and the retrofit work was undertaken at this property between October 2015 and December 2015.

Table 15: Some of the retrofit measures undertaken to tackle fabric heat loss

D10	Construction information	Retrofit measures
Walls	Cavity wall, partially filled	Cavity Wall insulation top up and 120mm EWI (brick effect render)
Roof	100mm uneven insulation	Topped up to 320mm
Floor	Solid floor	None
Doors/windows	Double glazed; More than 25 years old - very draughty and poorly installed	Insulated reveals where space allowed, draught-stripping
Eaves	Sloped eaves poorly insulated	Installation of trays to allow for ventilation, insulation top up

Table 15 shows the condition of D10 prior to retrofit and highlights some of the measures that were added to tackle fabric heat loss.

8.3 Thermal imaging survey results

Areas that were identified as particularly vulnerable to heat loss in property D10, and shown on the pre-retrofit thermal images below were: the bay window trim, the junction between the wall and the skirting, the window and front door reveals and the eaves ends.

8.3.1. Walls

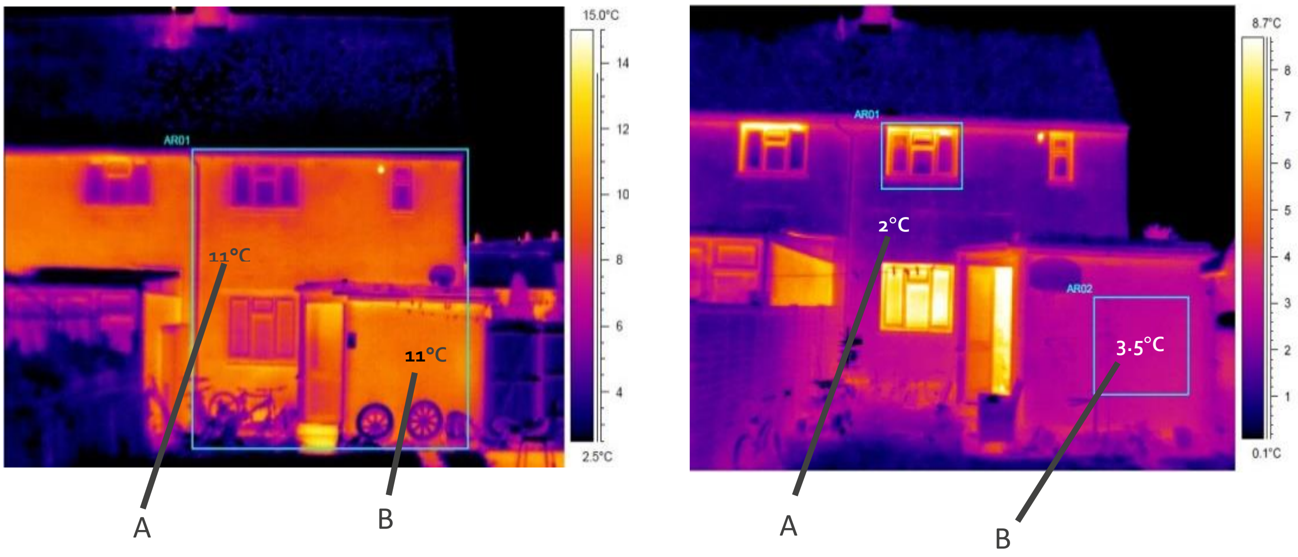


Figure 42: Thermal images of the front of D10 prior to retrofit (left) and post (right)

Figure 42 shows the external walls of D10 before and after retrofit was undertaken. Point A demonstrated the reduction in heat loss that had been achieved with cavity wall insulation topped up as well as the installation of external wall insulation; 11°C to 2°C, or 82%. Temperatures had consistently been reduced across the wall area post insulation installation, which showed that retrofit had been successful.

Point B showed the heat loss from the ground floor extension, this area was not retrofitted. The image on the left demonstrates that there was significant heat loss from the extension; the same as the exterior wall. The image on the right, taken post-retrofit, shows that the internal insulation on the main house had reduced the heat loss from the extension. It should be noted that the extension was not inhabited and was used as a storage room.

8.3.2. Doors/windows

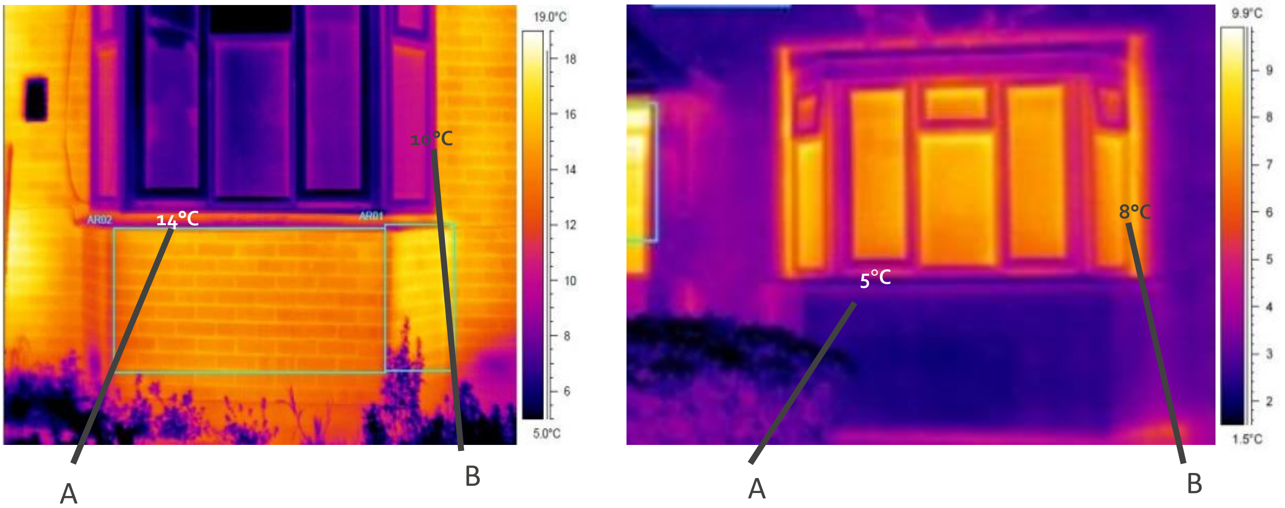


Figure 43: Thermal images of the front window on D10 prior to retrofit (left) and post (right)

Figure 43 is a thermal image depicting the front window of D10. The temperature of the window sill and jamb had been reduced from 14°C to 5°C (Point A) and 10°C to 8°C (point B) respectively; these were areas that were targeted for draught-stripping. Retrofit was effective in this instance as heat loss had been reduced.

8.3.3. Eaves

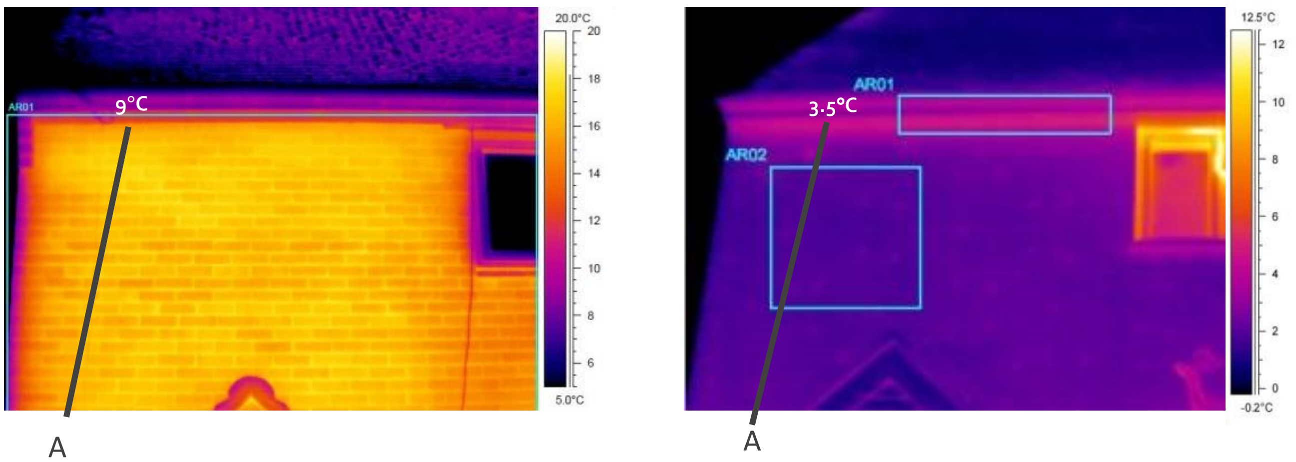


Figure 44: Thermal images of the eaves on D10 prior to retrofit (left) and post (right)

Figure 44 shows thermal images for the eave area on the front of D10 before and after retrofit, where external insulation was installed. There had been an improvement of 5.5°C at point A. This equates to a 61% reduction in heat loss and demonstrated that the retrofit measures had been effective.

8.3.4. Doorways

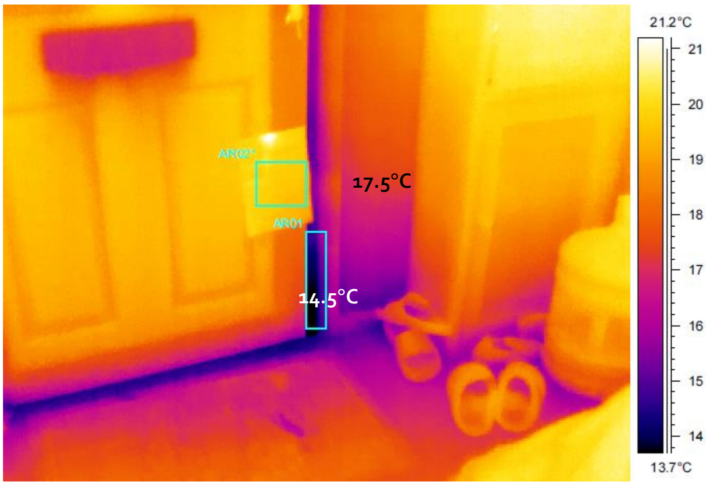


Figure 45: Thermal image of the front door and hallway in D10

Figure 45 highlights an area of thermal bridging between the door and the surrounding space in property D10. The area highlighted as AR01 indicates that temperatures were lower than the surrounding areas, 14.5°C compared to 17.5°C with a TI value of 0.41. There was a slight risk of condensation and mould growth. Even though draught-stripping measures were installed around the door, the heat loss had not been resolved completely.

8.3.5. Sloped internal ceiling

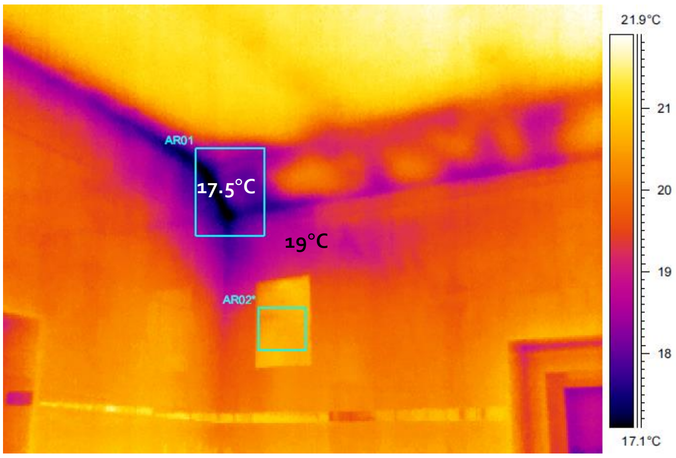


Figure 46: Thermal image of the corner of the bathroom in D10

Figure 46 shows the thermal bridging occurred at the corner of the sloped internal ceiling and the external wall in property D10. Temperatures in the corner, 17.5°C, were lower than the surrounding areas, 19°C, which resulted in a TI value of 0.71. It indicated that there was a risk of condensation and mould growth due to an existing condition (insulation installed unevenly prior to the retrofit works).

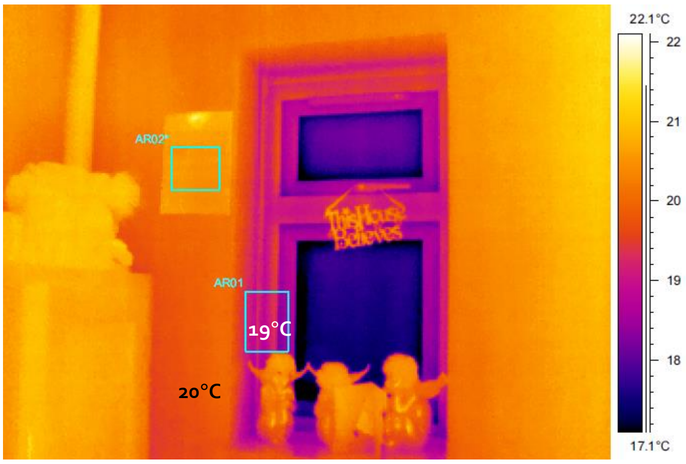


Figure 47: Thermal image of the hallway of property D10

Figure 47 shows the hallway in property D10 where retrofit had been successful in reducing heat loss and areas of thermal bridging. The TI value of 0.88 and temperature of 19°C in the area surrounding the window meant that heat loss had been reduced and damp was less likely to form.

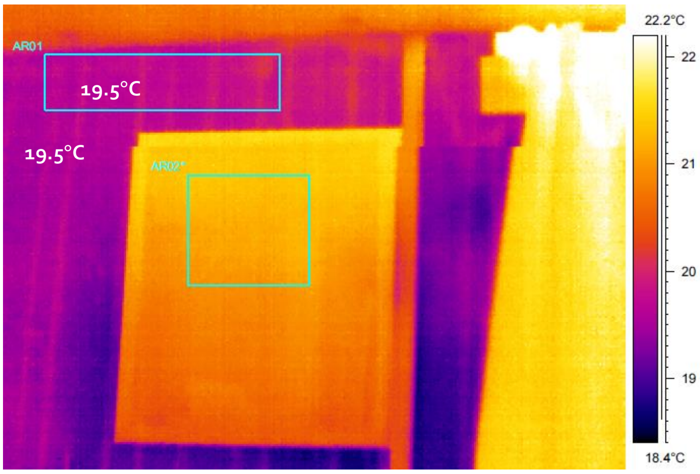


Figure 48: Thermal image of the living room of property D10

Figure 48 shows an insulated wall in the living room of property D6. Temperatures of 19°C and a TI value of 0.89 demonstrated that retrofit measures had been successful.

8.4 Environmental data analysis with the occupant interview

The following section includes findings from the environmental analysis, coupled with the information received from the occupant interview.

8.4.1. Selection of data for analysis

Retrofit work was undertaken between October 2015 and December 2015 and therefore the following pre and post-retrofit datasets were selected for data analysis / comparison:

Table 16: period chosen for data analysis

	Monitoring Period
Pre-retrofit	Nov 2014 - Feb 2015
Post-retrofit	Nov 2016 - Feb 2017

It should also be noted that data from the back-up battery-powered data loggers was used as post-retrofit dataset, due to a fault with the real time monitoring system that was installed at D10.

8.4.2. Key findings

Results showed that the average room temperatures prior to the retrofit were usually around 20°C in the monitored bedroom and the bathroom, and no data was available in the living room and kitchen. Post-retrofit temperatures were around 22°C across all rooms.

Table 17: Average internal temperatures in D10 pre- and post-retrofit

Period	**Average room temperature in $^{\circ}$C over the monitoring period**				**Average External Temperature over the monitoring period ($^{\circ}$C)**
	D10 Bedroom	**D10 Bathroom**	**D10 Living Room**	**D10 Kitchen**	
Nov 2014 – Feb 2015 (pre-retrofit)	19.4	19.4	n/a	n/a	6.3
Nov 2016 – Feb 2017 (post-retrofit)	21.7	21.5	22.4	22.8	5.9

In terms of energy usage, the occupant (the mother) stated that she had had to change the thermostat and timer settings since the retrofit work was undertaken. The heating was turned on less frequently post-retrofit. She also felt that some of the rooms required less heating post-retrofit; however, she did not seem to understand how to use the TRVs (and had never done so in the past) and she had been only using the thermostat to adjust the temperatures. The occupant stated in the interview that she understood a need to change some of her old habits and that she was trying to adapt to the retrofitted home.

Comparison between pre and post-retrofit data also indicated a reduction in the relative humidity levels in the rooms.

Table 18: Average relative humidity in D10 pre and post-retrofit

Period	Average relative humidity (RH) in % over the monitoring period				Average External RH over the monitoring period (%)
	D10 Bedroom	D10 Bathroom	D10 Living Room	D10 Kitchen	
Nov 2014 – Feb 2015 (pre-retrofit)	47.9	51.0	n/a	n/a	90.1
Nov 2016 – Feb 2017 (post-retrofit)	40.6	43.1	36.3	39.5	90.8

The graphs below show the frequency of the CO_2 levels in the living room and the bedroom collected from the real time loggers. From the very limited data available on the CO_2 levels, it could still be deduced that the CO_2 levels were below the ASHRAE threshold of 1,000 ppm which suggested good air exchange, although the occupant stated that they would regularly open windows out of habit.

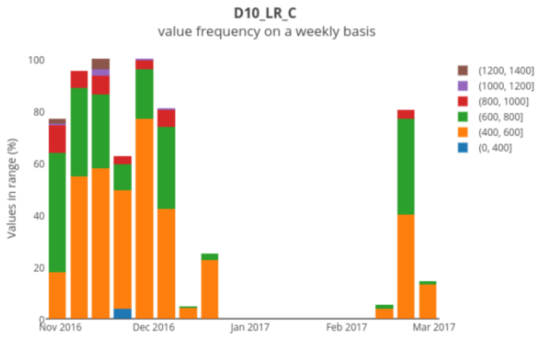


Figure 49: Frequency chart for CO_2 levels in D10's living room

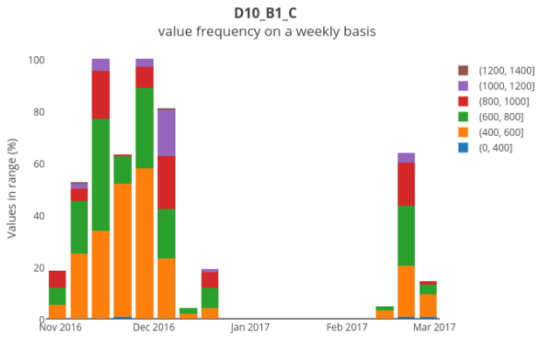
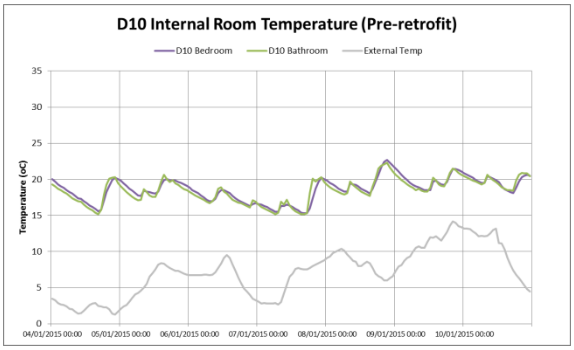


Figure 50: Frequency chart for CO_2 levels in D10's bedroom

8.4.3. More detailed observations of D10

Data from one week from the pre-retrofit period and one week from the post-retrofit period was selected for closer inspection, taking into account the similarity between the external weather conditions (similar average external temperature and RH, and similar estimated HDH for the week), as shown below. Data showed that the average room temperatures in the rooms had increased and the average relative humidity levels had decreased in the post-retrofit scenario.



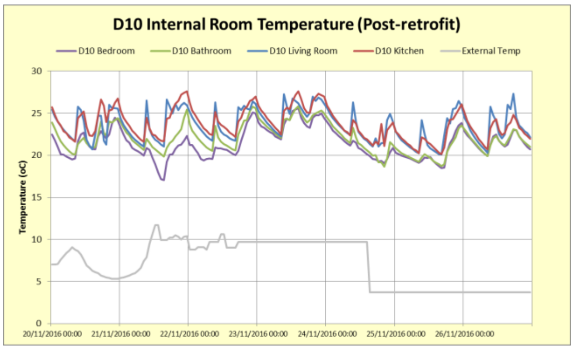
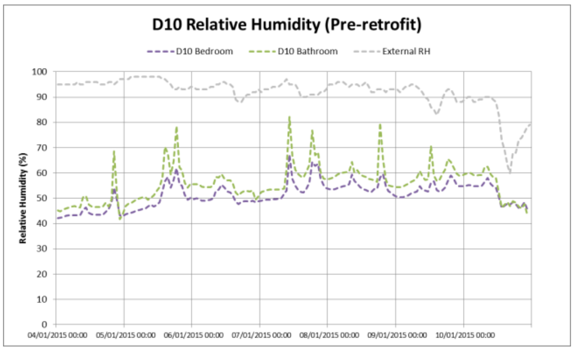


Figure 51: Average internal temp in D10 for a week pre-retrofit Figure 52: Average internal temp in D10 for a week post-retrofit



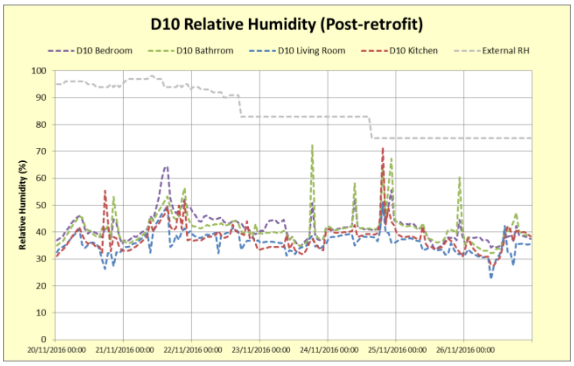
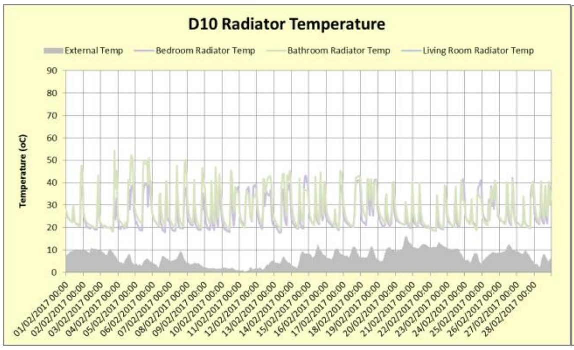


Figure 53: Average RH in D10 for a week pre-retrofit *Figure 54: Average RH in D10 for a week post-retrofit*

The graphs below confirmed that that all the radiators in all the rooms were turned on at the same time.



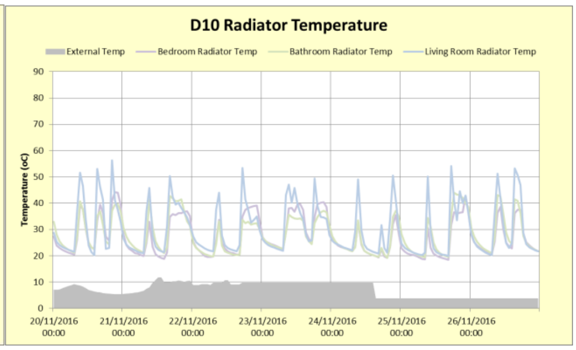


Figure 55: Average radiator temperatures in D10 in Feb 2017 *Figure 56: Average radiator temperatures in D10 for a week*

8.5 Energy consumption comparison

	Start of period	End of period	Gas Consumption (from actual readings)	Carbon dioxide emission (derived using emission factors)
Pre-retrofit	22/06/2013	17/06/2014	15,578 kWh	2866 $kgCO_2$
Post-retrofit	02/07/2015	12/06/2016	12,505 kWh	1300 $kgCO_2$
Difference			3,073 kWh	566 $kgCO_2$ (19% reduction)

It was not possible to obtain data for a 12-month period post-retrofit (as the data is only available up to June 2016), and therefore the period from between July 2015 and June 2016 was used. The gas consumption is around 12,500kWh post-retrofit, which is around Ofgem's national average gas consumption figures. The figures from pre and post retrofit suggest that there could be a potential carbon dioxide savings of 19% or more.

The occupant stated that there were a number of benefits from having the retrofit works done, including a more comfortable house with a better appearance, less damp in the house, as well as the savings on the gas bills, which had been lower than the electricity ones since retrofit. Even though the works took longer to finish than she expected, because of some issues in the management from the contractor's side, she felt that she would highly recommend having a house retrofitted to friends and family.

8.6 Summary

D10 was one of the smaller properties that had retrofit works undertaken as part of the Scaling up Retrofit. It was occupied by a family of four.

The occupant agreed that there was a need to change some of her old habits and that she was trying to adapt to the retrofitted home. The environmental data analysis showed a higher internal room temperature post-retrofit, in line. Less gas consumption was found post-retrofit which confirmed that less energy was required to maintain the desired temperature of the house as a result of retrofit.

The main occupant said that after the retrofit works was completed, the heating system was set on a timer and she would sometimes manually override the settings by turning the thermostat down when the temperature in the house was deemed to be too high. TRV controls were not used by the occupants.

The gas consumption analysis indicated that approximately 19% of energy savings was achieved through the retrofit work. However, it was clear from the interviews that there were other opportunities to further reduce the energy consumption, e.g. using the TRVs settings, changing window opening habits.

9. Conclusion

By overlaying the quantitative data with the qualitative findings, a rounded understanding began to emerge on the impact to the building performance as well as the changes to the residents' behaviour after the retrofit works were undertaken at the four properties.

D1 was one of the bigger properties with the largest number of occupants including a number of young children. D3 was also a bigger property, with one of the occupants having health conditions that required specific needs. D6 was one of the smaller properties with occupants that were in full time employment and were only at home during the evenings and some of the weekends. D10 was also a smaller property, but occupied by a family of four.

In summary, the thermal imaging survey showed that there was a general improvement of all the thermal fabric retrofitted as part of the project across all properties. The external walls were showing a drop of temperature from 20°C to 3°C on average post-retrofit. Other areas that were of particular concerns of thermal bridging had also experienced a substantial improvement; these include eaves, below damp proof course (DPC) areas, and windows and doors reveals (where space allowed). However, there could be opportunities for further improving some of the junctions and service penetration details in future projects.

The air test results in one property also confirmed air loss routes were addressed and resolved by the retrofit work, which meant that the property became more air-tight after the retrofit works were completed.

The responses from the occupants indicated that they were generally very happy with the improvement to their houses after the retrofit works were undertaken, in terms of their personal comfort and the appearance of their property.

The retrofit works had also addressed the issues with mould growth within the properties and reduced the risk of condensation, which in some cases was a key concern for the occupants.

There were different heating demands from each household; some required more heating because of specific needs (for example, the health condition of the occupant at D3, or the larger household with young children at D1). In addition, they had different behaviour towards heating usage; some prefer to set the heating on a timer, while some prefer to turn the heating on manually as required.

Regardless of the difference in heating demands and behaviour towards heating usage, most of the occupants stated that their house could heat up quicker and be kept warmer for longer post-retrofit and that this was desired in the winter period as they did not need to turn on the heating as often. They also stated that the cost of utility bills had been reduced. Our data analysis confirmed that most of the houses were maintained at a comfortable temperature with reduced use of the heating system.

Our analysis on energy consumption from the energy bills showed that two of the four properties (D3 and D10) had a significant reduction of energy consumption post-retrofit. D1 saw a slightly lower reduction but it was confirmed at the interview that it was a trade-off between personal comfort and energy consumption as the occupants were unable to heat the home as they desired prior to retrofit. D6 showed little reduction in consumption but it could be explained by the fact that the occupants of this home used significantly less gas than the average household to begin with.

However, it was clear from the interview that the occupants were not familiar with the use of TRV controls and did not use them to adjust the rooms to different desired temperatures, and had on occasions opened windows to cool down the room, instead of turning the heating off. If more training is given to the occupants on using the heating system controls, there may be opportunity to further reduce the energy consumption.

It is evident through the evaluation of this study that the correct installation of the retrofit measures can improve the thermal performance of the property, provide desired comfort to the occupants, drive down the cost of energy bills and in return the reduction of energy consumption.

10. Appendices

Environmental data analysis, air permeability report and thermal imaging reports and raw datasets

11. Appendix A - Thermal Imaging Reports

12. Appendix B - Air Permeability Test Report

13. Appendix C - Raw Datasets