Core cities Green Deal monitoring project

Prepared for the Department of Energy and Climate Change

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LEEDS BECKETT UNIVERSITY

Leeds Sustainability Institute

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Contributors

Principal Investigator	Professor Chris Gorse
Co-Investigator	Dr David Glew
Researchers and authors	Professor David Johnston, Dr Fiona Fylan, Dominic Miles-Shenton, Melanie Smith, Matthew Brooke-Peat, David Farmer, Dr Anne Stafford, Dr James Parker, Martin Fletcher, Felix Thomas

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Executive Summary

Leeds was designated a core city for trialling the Government's Green Deal domestic energy efficiency policy. Leeds Beckett University undertook a monitoring and testing program on 65 dwellings to investigate the effectiveness of the insulation measures installed and to understand any underperformance. This report outlines the findings from a series of investigations including; surveys, air tightness tests, co heating tests, *in situ* U-value tests, hygrothermal and thermal bridging modelling, in use monitoring and occupant interviews.

The surveys revealed that the 'whole house approach' to retrofit was, more often, missing, and quality assurance around insulation detailing was regularly absent, leading to avoidable errors and potentially embedding problems in the installations. Furthermore, moisture issues were, in the majority of instances, over-looked or made worse despite over half the sample having some form of damp. Despite this, energy savings were observed and the appearance of the dwellings were improved, thus apparent satisfaction was generally high, even though the installs were imperfect and moisture problems were introduced.

Hygrothermal modelling of IWI cases suggests that thermal bridging at party walls can increase by more than 60% and that there could be potential for rot to embedded timbers.

Insulation was recorded to reduce background ventilation of the dwellings by around 25% (a factor unaccounted for in government energy models), although some dwellings were still left with air tightness levels worse than modern day UK Building Regulations limits and replacing wet plaster with IWI was seen to undermine the performance of the insulation.

The heat loss coefficient of three homes were tested and showed improvements of 25% and 56% for full retrofits with IWI, and 8% for a party wall retrofit; ¾ of these savings were achieved by fabric improvements and the final quarter from incidentally making dwellings more air tight.

The before and after in use monitoring suggested the average savings in energy consumption from all retrofit types (EWI, IWI or other) were between 20% and 29%, although small sampling periods limits the certainty of the results. More reliably it was observed that comfort conditions improved; before the retrofit, 14 of the homes were experiencing discomfort from cold; the retrofit brought on average $^2/_3$ of uncomfortable homes into more reasonable comfort bands.

Nearly all of the occupants had positive experiences, although no householders had to pay for the retrofit, reporting being warmer, bringing unused rooms back into operation and feeling more pride in their homes and communities. A variety of perceptions and behaviours were observed around set point temperatures, use of heating controls and motivations for using energy, all of which contribute to make a complex policy landscape.

There is huge potential for domestic retrofit and although this research suggests the current policy not maximising benefits or minimising risks, it is undoubtedly beneficial in many ways.

Extended Summary

Findings

Surveys

It is often claimed that a whole house approach is desirable or even necessary for successful retrofits, however this project observed very few occasions where this was put into practice. In most instances wall insulation was installed without addressing failing or substandard loft insulation, the ground floor was almost always left uninsulated and the condition of the original wall was usually not obviously assessed or repaired prior to the installation.

Similarly, the impact of the retrofit on the moisture and ventilation dynamics in the houses was usually ignored. Major concerns for dwelling retrofits centre on moisture problems. In this project it was revealed that over half the properties had some damp issues. This is particularly of concern since all the properties had timber joists and in some dwellings air bricks were covered over by the insulation, there were no instances of trickle vents being installed or repaired and no additional extract fans were provided. Unintended consequences could manifest if these issues are not addressed and anecdotal evidence was found that condensation was more of a problem post retrofit in some dwellings. However, while basic guidance on ventilation exists, currently there is a lack of research to inform effective standard ventilation strategies in retrofit projects that could be relied on in such situations.

Instances of poor practice were also observed in the installation, for example cut-outs were made in the insulation rather than relocating gutters, flues and other items attached to walls; this creates thermal bridges and inconsistencies in the insulation layer. In addition, there seemed to be an inability or unwillingness to effectively adapt the designs to architectural or building features resulting in many instances of thermal bridging especially at eaves, the ground floor, around sills and jambs and, especially for internal wall insulation (IWI), behind kitchen and bathroom units. Often the number of trades on site resulted in details being missed such as sealing around service penetrations. All of these issues will have affected the performance of the retrofit.

Airtightness

The blower door tests undertaken in this project confirm an important previous finding; solid walls are not solid, they have finger cavities and can act as thermal bypasses.

The dwellings in this project in general had particularly poor airtightness levels before retrofit. The retrofits improved airtightness in the dwellings by, on average 25%; however, it was apparent that there was still room for improvement, with ten of the eighteen tested after retrofit having air tightness levels worse than the minimum allowable for new builds in the UK.

The greatest improvements in airtightness were achieved where a whole house approach was taken and specific designs for the air barrier were made and a maximum improvement of 61% was measured. Staged retrofits of IWI are likely to result in dwellings with relatively unimproved airtightness that can undermine its success.

Particular problems with air tightness were found where wet plaster was replaced with plaster board on dabs of plaster, sealing around services was not performed and where air leakage pathways that were not associated with the retrofit were not improved.

Co heating tests

The IWI retrofits achieved reductions in heat loss coefficients (HLC) of between 25% and 56%. Party wall cavity fill reduced HLC by only 8%, however, as a low cost measure party wall insulation may have significant potential as a widespread retrofit measure.

Of the reductions, fabric improvements were responsible for roughly 70% to 80%, with the remaining 20% to 30% coming from improved air tightness. The wide range in performance of the IWI is likely to be due to the approach taken by the installers, for example, contractors with a whole house approach to the retrofit and who give attention to detail to air barriers, achieve better outcomes than retrofits performed by sub-contractors. It was also found that reductions to HLC achieved by improvements in air tightness could in some instances be roughly equivalent in magnitude to that achieved by IWI and in excess of the improvements achieved by party wall cavity fill.

Modelling

The modelling undertaken in this project revealed that unintended consequences with IWI could include reducing neighbours' internal wall surface temperature (to a level that may promote condensation), and that thermal bridging at party walls can increase by more than 60%. It also suggests that because of reduced heat input into the wall and because IWI acts as a moisture barrier there could be potential for rot to embedded timbers. The use of IWI requires further longitudinal monitoring to explore the impact of systematic intervention and the ability to mitigate and control long-term moisture risks.

In-use monitoring

Of the forty-seven dwellings that were monitored, eighteen were deemed to have sufficient quality data to interpret the magnitude of the retrofit improvements. Thirteen had solid concrete walls, five had solid brick walls seventeen of the retrofits had External Wall Insulation

(EWI) as the primary measure, one was Loft Insulation (LI). Mean savings were estimated to be between 4% and 29% depending on the assessment method chosen, as indicated by the negative values in Table A. Although analysis the difference between the before and after energy efficiency may not be statistically significant, these average reductions for solid wall insulation are in the same order of magnitude or slightly higher as those identified in the National Energy Efficiency Data framework (NEED).

Table A, Average change in energy consumption achieved by retrofit

Analysis method		Mean % change
Power Temperature Gradient (PTG)	n=11	-28%
kWh / Heating Degree Day (HDD)	n=18	-4%
kWh / Dwelling Heating Demand (DHD)	n=18	-20%
Heating Demand Gradient (HDG)	n=13	-29%

When excluding analysis that assumes the dwelling set point temperatures, i.e. excluding and Heating Degree Day (HDD) methods, the range in mean savings are likely to be around 20% to 29%. Thus in this project HDD calculations may have underestimated the level of savings achieved. Using PTG, DHD or DHG may provide more robust analysis although for individual dwellings the predicted savings between each method could vary substantially.

To observe the variations in the dwelling performance one must look beyond the simple mean. Performance was in reality intrinsically linked to building's original condition and the occupant interactions which in some instance resulted in the dwellings appearing to use more energy after the retrofit. This highlights the importance of having sufficiently large sample sizes when conducting research into retrofits and emphasises that difficulty in being able to accurately predict savings that may be achieved on an individual dwelling level. The distribution of variation in performance is shown in Figure A.

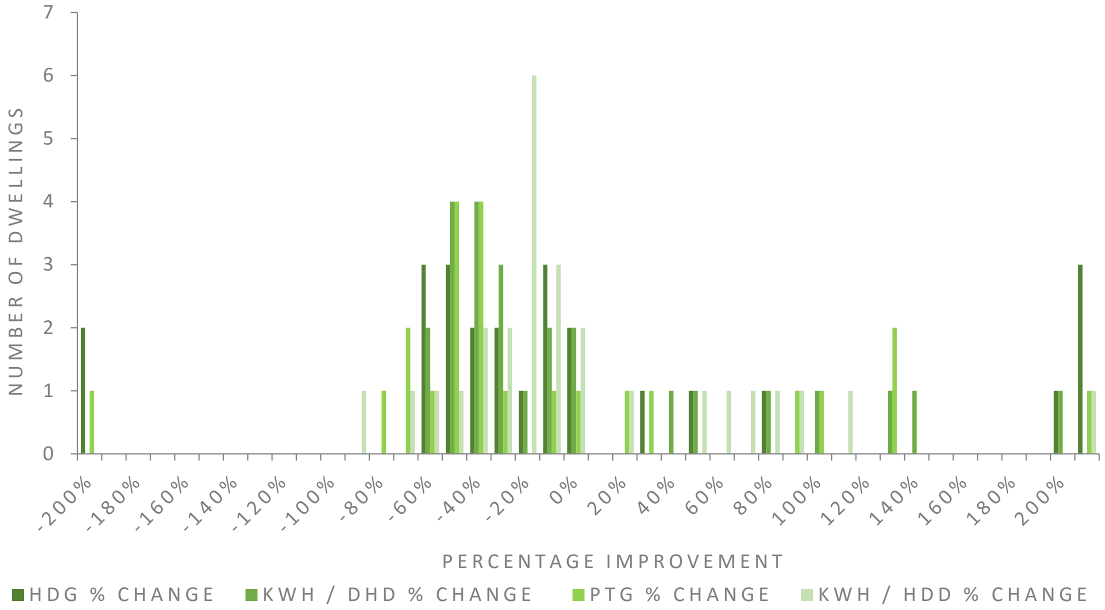

Figure A, Retrofit impact on energy efficiency (a negative result represents an improvement)

Comfort taking

Comfort taking is the idea that retrofits will appear less successful as people find it easier and choose to heat their homes more. The monitoring also highlighted that fourteen houses would be considered uncomfortably cold before the retrofit took place. After the retrofit in the eight of these for which data are available, five were brought into a comfort band deemed to be acceptable. In addition, it was observed in five further homes that were already achieving some degree of comfort the retrofit further improved the comfort level. This suggests that in ten of the dwellings studied, some degree of comfort taking may have taken place.

Behavioural study

Nearly all of the occupants had positive experiences of the retrofit they received (although they had usually not paid for the installation) and described their homes as being warmer, easier and cheaper to heat as they retained heat for longer and in some cases were less draughty. Some described how they were able to heat rooms that they previously left cold and unused and some thought their homes were less damp as a result. The occupant survey showed a significant increase in how comfortable occupants rated the temperature in their home, and a significant decrease in ratings of it being too cold. There was no change in their ratings of their home becoming too warm. In addition, one of the major occupant centred benefits of the retrofits was the indirect improvements to the streetscape, making the appearance of the homes and neighbourhood more pleasant and enjoyable to live in.

The behavioural research also revealed that there is a very wide spread of beliefs about energy and heating behaviours, even in similar house types; this is one of the influences affecting the apparent success of the retrofit. Some occupants accepted having cold rooms or closing off parts of their house as an energy saving measure, while others believed they had no choice but to provide a warm home for their families and pets. Many were anxious about maintaining control over their energy bills. Moreover, it identified that occupants often struggle to understand how to use their heating controls, which had an adverse effect on their consumption or their thermal comfort. Many householders deemed it necessary to make use of secondary heating sources, which are generally more carbon intensive than gas central heating, and thus an indirect benefit of the retrofits may be a reduction in the use of carbon intensive secondary heating.

Policy considerations

There are several observations highlighted in the discussion section of the report that may inform future policy recommendations, including:

- Alternative low cost measures (e.g. party wall fill and air tightness) are underutilised;
- For accurate financial retrofit payback predictions, air tightness tests are needed;
- A whole house approach is often ignored and remedial work not undertaken;
- Installer quality process control is not robust;
- Fuel bill savings were generally achieved even in imperfect installations
- Variability in dwelling energy behaviours means retrofit success varies substantially;
- Unintended consequences may manifest in a large number of retrofitted homes;
- Ventilation issues and continuity of insulation is usually ignored in retrofit;
- Huge demand but significant uncertainty from registered social landlords (RSL) for retrofits; and
- Wider benefits to occupants of improved dwelling appearance were greatly valued.

1 What is the Core Cities Green Deal monitoring project?

Leeds was designated a core city for trialling the Government's Green Deal domestic energy efficiency policy; as part of this the Department of Energy and Climate Change (DECC) funded Leeds Beckett University to undertake a monitoring and testing program to investigate the effectiveness of retrofit measures installed.

1.1 Project scope

Initially Leeds City Council proposed that 100 homes could be found for the research project to run between 2013 and 2015. These were to be predominantly social housing consisting of a limited number of archetypes including solid brick Victorian back-to-back and through terraces as well as a selection of no-fines concrete properties.

Changes to the planned projects, measures, timescales, funding and government policy however limited recruitment opportunities. Leeds City Council were not able to resource a recruitment drive as planned and so Leeds Beckett University took on this additional role to ensure the project could continue using local contacts with registered social landlords (RSL). As a result, nineteen dwellings were recruited in 2013/14 and a further twenty-five in 2014/15. An extension was granted by the DECC to extend the monitoring period into 2015/16, from which an additional fifteen dwellings were recruited providing a total of 63 dwellings for the various testing procedures as summarised in Table 1-1.

Table 1-1 Overview of dwellings

Test procedure	Number of dwellings[1]
Co-heating test	4
Air tightness test	15
U-value measurement	7
Moisture monitoring and modelling	3
Occupant behaviour study	33
In use monitoring	47
Total dwellings	**65**

1.2 Project rationale

The need to improve the energy efficiency of the UK housing stock is clear (Palmer and Cooper, 2013, Bell and Lowe, 2000, DECC, 2012c, ZCH, 2014, DCLG, 2015). This project is designed around two questions. The first is to assess how well refurbishments are currently performing using in-situ measurements. These can then be compared to the benchmark savings being reported in the National Energy Efficiency Database (NEED) data. NEED

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[1] Some dwellings had multiple tests

incorporates building metadata, occupant demographics and annualised energy consumption information for all dwellings in the UK. It is possible to provide an aggregated high level assessment of the efficacy of various types of refurbishment interventions that have taken place as a result of previous government schemes, especially loft and cavity wall fills and to a lesser extent solid wall insulation (SWI).

Analysis of NEED data shows there is a performance gap meaning refurbishments do not achieve their optimum savings. The performance gap phenomenon has been well documented in domestic new builds and retrofits (Wingfield et al., 2007, NMN, 2012, Carbon Trust, 2011, Innovate UK, 2016a). NEED savings are used to establish benchmarks for refurbishments and their respective in-use factors for government retrofit policy (DECC, 2012b) however developing solutions to minimise the gap requires a more detailed understanding of specific case studies.

This leads on to the second question of this project which is to investigate what are the underlying causes behind the performance gap in the refurbished dwellings. To achieve this a range of detailed intensive field tests were undertaken, site visits were made and qualitative data was collected from the occupants to complement the in-use monitoring of actual performance. Findings may be used to inform future retrofit programs and provide guidance to policy makers, installers, and householders.

This document collates the results of the separate research investigations described in Table 1-1, while more detailed results and analysis of each of these are available in the appendices. This document discusses the links between the findings, comments on the implications for the refurbishment sector, identifies areas for future research and explores policy implications.

1.3 Project aim and research objectives

The project aim is to help improve the quality of domestic retrofit installations in the UK. It has several specific objectives:

1.3.1 Quantify retrofit success

Where possible degree day and degree day related analyses from in use monitoring data as well as thermal building performance tests (co heating tests, U-value measurements and air tightness testing) identify the before and after energy efficiency of the dwellings. These are benchmarked against savings found elsewhere for similar retrofits on similar building archetypes.

1.3.2 Identify underlying causes for the performance gap

The influence of several causal factors for the performance gap are discussed, namely comfort taking, occupant behaviour, influence of controls, workmanship, site processes, design and product quality.

1.4 The dwellings

The scale of the project was limited in the sense that it was important to obtain sufficient detail from case studies as opposed to merely capturing a statistically large sample. There are necessarily several dwelling archetypes represented in the sample since the originally planned sample of dwellings did not materialise. This extends the scope of the investigation providing information on a wider range of property types, which may be useful, however it also reduces repeatability and representativeness of the sample in relation to the UK housing stock as a whole. Figure 1-1 describes the different archetypes and their primary retrofit measure of either external wall insulation (EWI), internal wall insulation (IWI), party wall insulation (PWI), Edufoam thin cavity insulation, or only air tightness sealing.

The archetypes reflect those commonly found in Leeds and the wider Yorkshire region, namely solid brick wall properties; predominantly Victorian *back to back* and *through terraces*, as well as a range of post war concrete dwellings. This is not therefore a representative study for the UK housing stock as a whole, however it does particularly address solid wall properties for which fewer data sets exist regarding retrofits in NEED and for which there are higher reported incidents of unintended consequences. It is therefore thought that the sample targets some of the most problematic housing types and the results should therefore have impact.

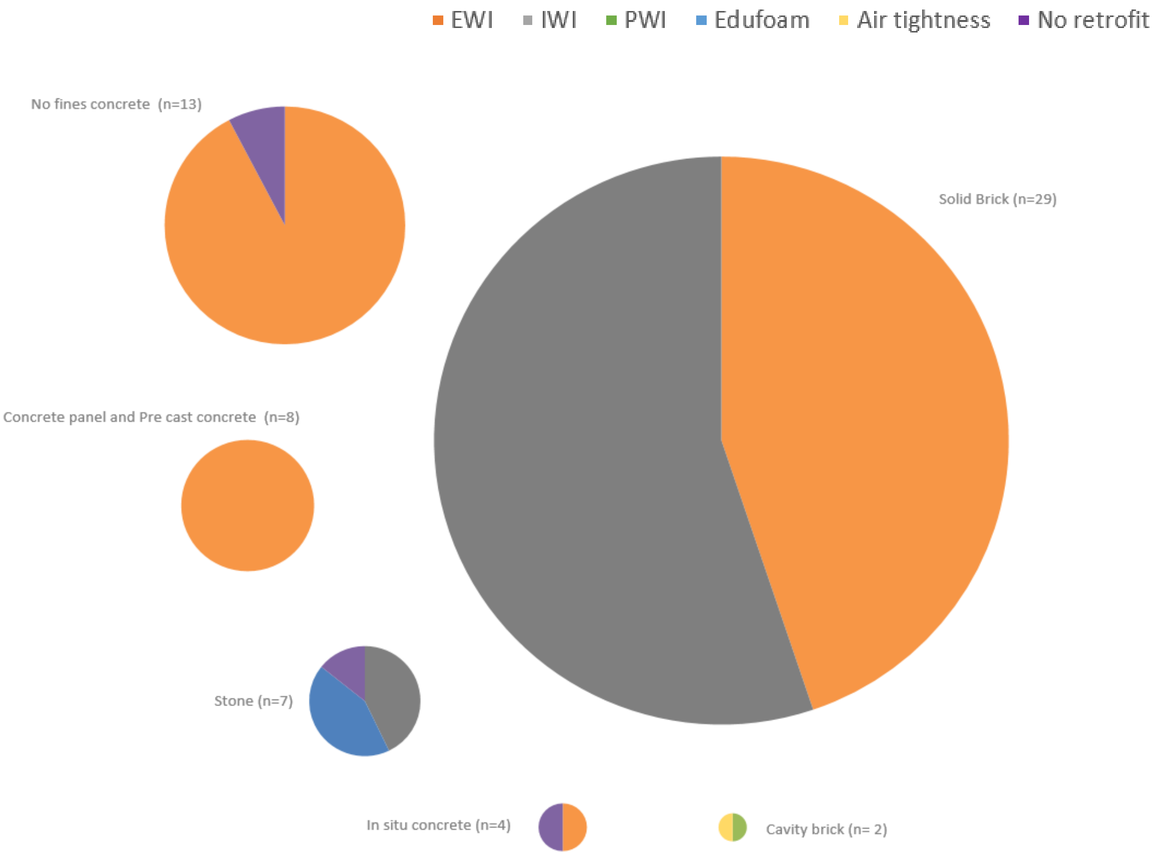

Figure 1-1 Dwelling archetypes and primary retrofit measure

As can be seen in Figure 1-2 the dwelling samples were clustered predominantly around the City of Leeds, though some dwellings were recruited from further afield as the search of properties was extended.

Figure 1-2 Location of monitored dwellings (image taken from Energydeck platform)

1.5 The measures and monitoring

Figure 1-1, identified the range of primary measures that were undertaken on the dwellings, these are shown on a dwelling by dwelling level in Table 1-2. In some instances, multiple interventions were undertaken though the majority were simply EWI or IWI alone or in combination with one other measure. The majority of dwellings were solid wall properties hence there were no Cavity Wall Insulation (CWI) retrofits, excluding the one Party wall insulation (PWI). In addition, since RSLs provided the bulk of the sample these had often already had loft Insulation (LI) and new boilers fitted. It is also evident that for some dwellings, the retrofit program was either cancelled completely or was delayed beyond the scope of this project; where this happened it was possible to collect data for the before retrofit stage.

The variety of measures and the range of archetypes in the sample means that while some generalisations regarding overall retrofit improvements or the benefits of particular technologies on certain building types may be inferred it is perhaps more appropriate to investigate these dwellings as a series of similar case studies, from which specific findings can be drawn.

The letters in the “Dwelling ID” indicate the level of testing that was undertaken, where “C” represents a co heating test, “I” indicates that more intensive monitoring was undertaken (being either an air tightness test, U value test or moisture monitoring), and “E” identifies that in-use energy monitoring took place. The following sections will take each test methodology in turn and describe the methods and findings.

Table 1-2 Summary of dwelling retrofits

Dwelling ID	Wall type	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5
C-1	Solid Brick	IWI	Boiler			
C-2	Solid Brick	IWI	Boiler			
C-3	Cavity Brick	PWI	LI			
I-01	Solid Brick	IWI				
I-02	Solid Brick	IWI	LI	Windows	Floor	
I-03	Solid Brick	IWI				
I-04	Solid Brick	IWI	Boiler	Windows		
I-05	Solid Brick	IWI				
I-06	Solid Brick	IWI				
I-07	Solid Brick	IWI				
I-08	Solid Brick	EWI	IWI			
I-09	Stone	Edufoam				
I-10	Stone	Edufoam				
I-11	Stone	Edufoam				
I-12	Solid Brick	IWI				
I-13	Solid Brick	IWI				
I-14	Solid Brick	IWI				
I-15	Stone	IWI	LI	Windows	Floor	
E-1	No-fines concrete	EWI	LI			
E-2	No-fines concrete	EWI				
E-3	No-fines concrete	EWI				
E-4	Solid Brick	IWI	Boiler	LI	Windows	Controls
E-5	Solid Brick	IWI	Boiler	LI	Windows	Controls
E-6	Solid Brick	IWI	Boiler	LI	Windows	Controls
E-7	No-fines concrete	EWI	Boiler	Windows		
E-8	No-fines concrete	EWI	Boiler	Windows		
E-9	In-Situ Concrete	EWI				
E-10	In-Situ Concrete	None				
E-11	In-Situ Concrete	None				
E-12	Precast Concrete	EWI				
E-13	In-situ Concrete	EWI				
E-14	Concrete	EWI				
E-15	Concrete	EWI				
E-16	Concrete	EWI				
E-17	Stone	IWI	LI	Windows		
E-18	Solid Brick	EWI	IWI			
E-19	Solid Brick	EWI	IWI			
E-20	Solid Brick	EWI	IWI			
E-21	Solid Brick	EWI				
E-22	Solid Brick	EWI				
E-23	Solid Brick	EWI				
E-24	Stone	IWI				
E-25	No-fines concrete	EWI				
E-26	No-fines concrete	No retrofit				
E-27	Solid Brick	IWI				
E-28	Solid Brick	IWI				
E-29	Solid Brick	EWI				
E-30	Solid Brick	EWI				
E-31	Solid Brick	EWI				
E-32	Concrete panel	EWI				
E-33	No-fines concrete	EWI				
E-34	No-fines concrete	EWI				
E-35	No-fines concrete	EWI				
E-36	No-fines concrete	EWI				
E-37	No-fines concrete	EWI				
E-38	No-fines concrete	EWI				
E-39	Solid Brick	EWI				
E-40	Solid Brick	EWI				
E-41	Solid Brick	EWI				
E-42	Brick cavity	EWI				
E-43	Stone	IWI	Windows	Solar HW		
E-44	Concrete	EWI				
E-45	Concrete	EWI				
E-46	Concrete	EWI				
E-47	Stone	No retrofit				

2 Surveying techniques

2.1 Overview of surveys

The National Energy Efficiency Database (NEED) provides relatively high level information on the efficacy of various types of refurbishment interventions that have taken place as a result of previous government schemes. In order to assess the findings in relation to the actual property under test, a high level understanding of each property is required to understand how the building is constructed. Building surveys were therefore conducted on the properties. Surveys were based on the RICS Guidance Note "Surveys of Residential Property", broadly equivalent to the level one surveys described; essentially visual condition surveys, noting construction, age and condition, highlighting any obvious defects or problems, together with moisture meter readings and infra-red observation. The purpose was to provide property information for testing regimes and analyses on the properties and background understanding of findings arising. As far as practicable, each property was surveyed before and after intervention, but this was not always possible.

Eighty-four building surveys were conducted on 52 properties, 48 pre-refurbishment, nine during refurbishment and 27 post-refurbishment.

2.2 Surveys procedure and pro-forma

A standard procedure was established for the building surveys broadly in line with RICS guidance. A key aspect of these surveys is the ability to gather information on site quickly and without specialist equipment, so that reliable survey data can be reproduced by surveyors in the field. Pro-forma was created for use on site and records completed electronically following visits. The pro-forma was developed over time to capture additional useful information so the reports for later visits are more informed. Information was stored in each property file, including photographs, thermal images and site notes. An example can be seen in Appendix A

Some aspects were found to be essential for the analytical team. As well as collecting normal survey and construction data, the survey team was asked to note:

- floor areas of conditioned space (i.e. living space capable of being heated);
- storey heights;
- number of bedrooms; and
- fuel use for space and water heating, showers, cooking and secondary heating.

NEED highlighted that the number of bedrooms for a property gives a reasonable indication of likely energy consumption. When looking at consumption by property age, NEED states that older properties tended to reduce consumption by the greatest amount in the years between 2005 and 2012, with newer properties typically reducing consumption by less. An explanation for this might be that older properties have more potential for thermal upgrade enabling reduced energy consumption. However, NEED tempers this finding saying that this distinction is not as clear cut as with the other property attributes of floor area, property type and number of bedrooms. NEED took parameters from the Valuation Office Agency property attribute data as shown reproduced in Table 2-1. The data collected for this research therefore included age of property, type of property, floors areas, conditioned volumes and number of bedrooms. A further category of back-to-back in property type was added. Although constructed in a similar manner to terraces, the additional party wall can have an effect.

Table 2-1 VOA property attribute data

	Property age	Property type	Number of bedrooms	Floor area (m^2)
Categories	Pre - 1919	Detached	1	1 - 50
	1919 - 1944	Semi detached	2	51 - 100
	1945 - 1964	End terrace	3	101 - 150
	1965 - 1982	Mid terrace	4	151 - 200
	1983 - 1992	Bungalow	5+	200+
	1993 - 1999	Purpose built flat		
	Post 1999	Converted flat		

The basic construction of the properties was also of importance for the data analyses. To some extent, this can be deduced by age and type, in that for example a pre-1919 domestic property is likely to be solid brick or stone, however the 1945-1982 properties can include a number of different types of system build as well as traditional brick/block cavity walls.

2.3 Common findings regarding areas of concern

Common aspects of concern were found for interventions. These are summarised in tabular form at Table 2-2.

There was little evidence that walls in a poorer condition (e.g. damp ingress, failing rainwater goods, poor pointing, failing external render etc.) were routinely repaired prior to intervention apart from for individual properties with one-off upgrading.

Half the properties surveyed had levels of dampness viewed as of concern when tested with a simple moisture meter. The causes included rising damp, penetrating damp, service leaks and failing rainwater goods. Despite this, there was only one property surveyed which had included damp proofing in the intervention measures. The effect of insulating damp walls is currently under research by a number of bodies.

Timber was seen to be present in the external walls of all pre-1919 properties surveyed during intervention works, mainly floor joist ends and timber internal face lintels over doors and windows (external faces showed stone, brick or concrete lintels but the main loading tends to bear onto the internal face lintel). This commonly found timber is of interest when considering the work presented in the chapter on Hygrothermal behaviour.

Typical areas of concern relating to specific age and design of properties have been identified to avoid repeating building-in problems for future projects. Surveys revealed areas of gaps in the envelope of thermal insulation leading to thermal bridging. These have the potential to result in significant heat loss and, in the worst cases, surface condensation, interstitial condensation and mould growth as identified in the sections on “thermal bridging and hygrothermal behaviour” as well as other parts of this report. Worsening condensation was noted in a few properties post-intervention which at the time of the surveys had not yet resulted in visible mould growth.

Table 2-2 Summary of issues and challenges found for Base Cases

Base Cases	Intervention	1. Thermal breaks, isolation	2. Services and fittings	3. Element interfaces	4. Lack of insulation	5. Ventilation and uninsulated elements	6. Window and door openings	7. Concealed areas and party wall
Historic stone built	EWI	Listing - EWI not permitted	Where permitted, potential as below	Where permitted, potential as below	Where permitted, potential as below	Where permitted, potential as below	Where permitted, potential as below	Where permitted, potential as below
	IWI	Potential for increased frost damage to external face	Potential as below	Potential as below	Potential as below	Potential as below	Potential as below	Potential as below
Pre-1919 solid brick terrace and back-to backs	EWI	Thermal breaks introduced to top floor wall/ceiling junctions	Thermal breaks at insulation cut-outs at external pipes, services, walls etc.	Thermal breaks introduced to ground floor/wall junctions	Lack of insulation to ground floor over unconditioned basement	Thermal breaks introduced at uninsulated doors & stair soffits & spandrels to uninsulated basement	Window and door lintels, jambs and sills left uninsulated or with reduced insulation resulting in thermal bridging	Thermal break at party wall/external wall junctions as EWI not extended across to neighbouring property
	IWI	Thermal breaks introduced at intermediate floor/wall junctions	Air gaps introduced around service entries through external walls	Thermal breaks introduced to ground floor/wall junctions	Lack of insulation to ground floor over unconditioned basement	Thermal breaks introduced at uninsulated doors & stair soffits & spandrels to uninsulated basement	Window and door lintels, jambs and sills left uninsulated or with reduced insulation resulting in thermal bridging	External walls concealed behind bathroom and kitchen fittings not insulated creating thermal breaks
1919-1940s solid brick semis and terraces	EWI	Thermal breaks introduced to top floor wall/ceiling junctions particularly where rooms partially in roof space with eaves sloping soffits	Thermal breaks at insulation cut-outs at external pipes, services, externally accessed stores, walls etc.	Thermal breaks introduced to ground floor/wall junctions	Lack of improved floor &/or roof insulation	Lack of improved ventilation	Window and door lintels, jambs and sills left uninsulated or with reduced insulation resulting in thermal bridging	
	IWI	None surveyed						
1945-1970s system built, including flats, terraces and semis	EWI	Thermal breaks introduced to top floor wall/ceiling junctions	Thermal breaks at insulation cut-outs at external pipes, services, externally accessed stores, walls etc.	Thermal breaks introduced to ground floor/wall junctions	Lack of improved floor &/or roof insulation	Lack of improved room ventilation	Window and door lintels, jambs and sills left uninsulated or with reduced insulation resulting in thermal bridging	
	IWI	None surveyed						

2.3.1 Thermal breaks introduced to top floor wall-ceiling junctions for EWI

This was seen as an issue in pre-1919 solid brick terrace and back-to-backs, 1919-1940s solid brick semis and terraces, and 1945-1970s system built, including flats, terraces and semis where EWI is applied. Illustrative examples are given at Figure 2-1, Figure 2-2, Figure 2-3 and Figure 2-4. If the interventions do not include altering the roof, eaves and/or gutters, then the EWI is normally stopped lower than the internal top floor ceiling height due to the limited overhangs at eaves or the height position of the eaves. This was seen to result in reduced insulation affecting up to 400mm depth of wall at first floor ceiling levels, leading to thermal bridging, and possible future condensation and mould growth. Other reasons not to continue the EWI to the full extent of the external walls can be the external decorative features which either are required to remain for aesthetic purposes or which would be expensive to reproduce on the EWI. Where there is a room in the roof space, there might not be a problem as alternate measures can usually be applied in the roof voids. For other arrangements, however, a long horizontal band of thermal bridging results, as can be seen in the example thermal image in Figure 2-4.

Where the bedrooms are partially in the roof void, a sloping plastered soffit was normally applied at construction against the bottom section of the rafters as in Figure 2-2. This portion is not usually historically insulated and is not easy to insulate post construction.

In terraces, adjacent properties are sometimes built at different levels so that roof lines are not continuous and party walls become external walls. Where adjacent properties were in the same ownership and both properties had EWI applied, it was found that this part gable external wall was insulated with EWI. Where adjacent properties were not in the same ownership, and were not both insulated, this wall was not insulated as seen in Figure 2-1. If this wall encloses a conditioned space internally, e.g. an attic room, which does not have IWI applied internally, it forms a thermal bridge.

Figure 2-1 Thermal breaks introduced to top floor wall/ceiling junctions: pre-1919 terraces and back-to-backs

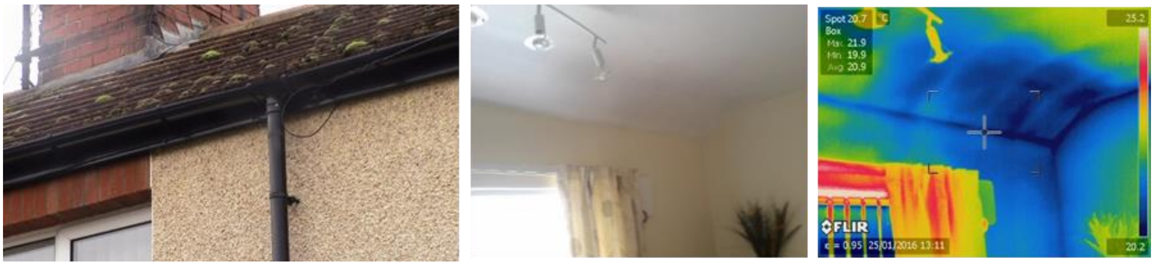

Figure 2-2 Thermal breaks introduced to top floor wall/ceiling junctions: the above three pictures are of the same property and show a typical 1919-1940s solid brick semis and terraces where the top floor is partially in the roof void with a sloping ceiling against the rafters

Figure 2-3 Thermal breaks introduced to top floor wall/ceiling junctions: 1945-1970s system built, including flats, terraces and semis. The roof, eaves and sometimes rainwater goods are not amended for the addition of EWI

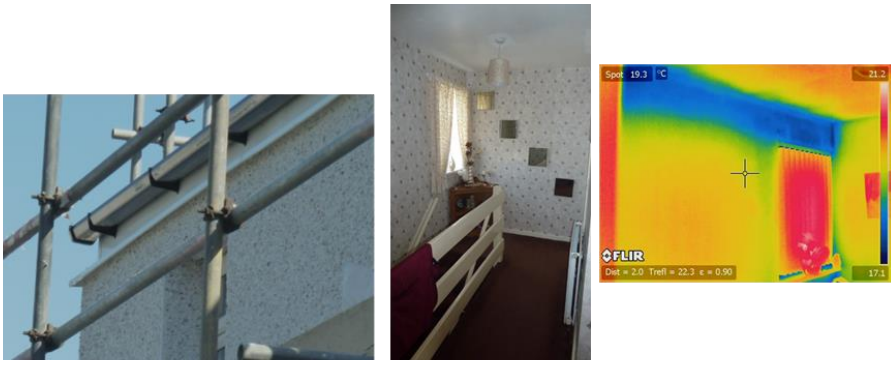

Figure 2-4 Thermal imaging for thermal break at top floor wall/ceiling junction for a 1970s no-fines end terrace

It is not unusual for rainwater goods to leak if the fixings become dislodged or blocked for any reason such as wind, build-up of debris/leaves, or even short term issues such as snow. For EWI, if seals between the top capping and the wall is ineffective, water ingress is able to seep between the insulation and original wall. See Figure 2-5 for an indication of the effect of this. The photographs show the rear to one pre-1919 terraced property where there was a leak at the gutter post-intervention and the first floor bedroom wall subsequently suffered from dampness. The flashing at eaves was repaired but the wall was continuing to dry out internally as the new EWI and render did not permit external drying out. As a rule of thumb, drying out typically takes one month per 25mm wall thickness.

Figure 2-5 Effects of water ingress through an imperfect seal at the top of EWI

2.3.2 Thermal breaks at insulation cut-outs for external pipes, services, walls externally accessed stores etc. for EWI

External insulation can also result in decisions to be made regarding moving rainwater and other goods and services positioned on the outside surfaces of walls. In those properties surveyed, generally the services were not moved but cut-outs were provided in the external insulation to accommodate the services. Similarly, garden walls and gates, attached to or butted up to the house wall, were not altered but the insulation cut to accommodate them. See Figure 2-6 and Figure 2-7. These cut-outs represent thermal bridges.

Figure 2-6 Thermal breaks at insulation cut-outs at external pipes, services, walls, doors, gates etc: these are typical for pre-1919 terraces where these services are not being amended in the EWI works

Figure 2-7 Thermal breaks at insulation cut-outs at external pipes, services, walls, doors etc: these are typical for 1945-1970s system built properties where these services are not being amended in the EWI works

Particularly for the system built terraces and flats, in-built externally accessed stores created thermal bridges to the conditioned rooms (rooms that are heated within the dwelling). The EWI was provided to the external walls, but not the store's internal walls. These internal walls abutted kitchens, halls and stairways and ground floor bedrooms. The stores were at the same temperature as the outside air due to the loose fitting external access door. There was therefore a heat loss directly through these walls which were treated as internal instead of external walls and not insulated.

Built-in balconies are a similar consideration. However, those seen had the EWI taken around the walls facing into the balcony i.e. they were treated as external walls and thermal bridging was not an issue.

2.3.3 Thermal breaks introduced to ground floor – wall junctions

There is a requirement under Building Regulation C2 that the walls shall adequately protect the building and the people from the harmful effects of ground moisture and precipitation. A standard way of achieving this is to ensure that applied surfaces to walls, including render and insulation which have the capacity to wick up moisture, are a minimum of 150mm above ground level and do not result in a bridge across a damp proof course (dpc). Dpcs themselves are usually placed at 150mm above ground level. For many properties, the finished internal floor level is at dpc level. This essentially means that there should be a break in externally applied insulation at this point. Some schemes provide for this break incorporating the equivalent of a dpc and then insulation which will not result in rising damp, or moisture penetrating internally, or else bridging of the dpc is applied below the house wall dpc level to ensure continuity of the thermal envelope. Most schemes however do not do this, resulting in a thermal break. See Figure 2-8.

Figure 2-8 Thermal breaks introduced to ground floor/wall junctions where the EWI is stopped around 150mm above ground level. The examples show a 1970 terrace, a pre-1919 terrace and a 1950s semi

For internal wall insulation (IWI), where the ground floor is insulated as part of the upgrade, this thermal break at the ground floor/external wall junction can be avoided. However where IWI was placed but there was no upgrade to the floor insulation, the thermal break existed.

Figure 2-9 shows typical ground floor/cellar ceilings after intervention of IWI. The floor joists tend to span party wall to party wall, with the last joist adjacent to the external wall with a gap around 25-50mm from the external wall. This gap is occasionally filled with offcuts or mineral wool, as shown in the central sketch, but not always. If there are gaps around these offcuts thermal bypass will occur. These thermal bridges may increase this risk of surface condensation.

Figure 2-9 Ground floor wall junction, especially typical at pre-1919 properties with basements. Some holes into floor voids are not taped/sealed. Where the floor between the basement and ground floor is not fully and carefully insulated, thermal bridges can occur

2.3.4 Lack of insulation to ground floor

Where properties had basements, there is usually easy access to insulate the floor between the unconditioned basement and the conditioned ground floor. For pre-1919 terraced and back-to-back properties, insulation to the ground floor was frequently applied. Sometimes this was not carried out as part of the scheme, or not fully completed including sealing the edges for air-tightness. For properties without a basement, no instances of upgrade of the ground floor were noted. All the post-1945 system built properties surveyed had uninsulated concrete ground floors.

This results in two adverse effects. Firstly, the floor becomes an area of exaggerated heat loss. Where the external door threshold consists on a single slab of stone or concrete, the heat loss at the internal threshold might be sufficient for condensation, see Figure 2-10.

Secondly, the occupant can feel cold due to stratification. Within normal ambient conditions, temperature differences between a person's head and feet of around 3 degrees centigrade are noticeable to humans, can affect their comfort, and can be uncomfortable (ASHRAE, 2013). The person does not necessarily perceive that their lower limbs are cooler, but they feel cold overall. When there is a warm, reasonably airtight building but with a heat loss through the ground floor, thermal stratification can occur with lower air temperatures close to the floor surface. For occupants who are less mobile, including elderly or less able people, the effect can be particularly problematic.

Where a lack of floor insulation is coupled with a thermal break at ground floor/wall junction as described above, the issue might be exacerbated.

Figure 2-10 Thermal breaks due to lack of insulation to ground floor and single slab door thresholds. These thresholds are found at suspended timber or solid concrete ground level floors

2.3.5 Thermal breaks introduced at uninsulated door and stair soffits and spandrels to uninsulated basements

A number of the refurbishment schemes did not include insulating the stair spandrel between the internal hall/passageway and the stairs down to the basement. Similarly the underside of the stairs to the first floor was not always insulated. Additionally, the door to the basement was not always replaced with an insulated and draught-sealed door.

These doors, spandrels and soffits form the interface between the unheated, uninsulated basement and the heated, insulated ground floor areas. Without the provision of insulation to these, there is a large thermal bridge between the unheated basement and the ground floor living area.

Figure 2-11 Interfaces between the unheated basement and heated ground floor which need to be insulated

2.3.6 Window and door lintels, jambs and sills left uninsulated or with reduced insulation resulting in thermal bridging

Whether wall insulation is applied internally or externally, there can be an issue around door and window openings. Insulation to the same depth as that applied to the street facing wall surfaces is usually too thick to apply at the jambs, sills and lintel soffits. If the doors and windows have already recently been replaced, the owner often does not want to replace them again to accommodate a thick layer of insulation to all four edges. If the doors and windows are to be replaced, the required reduced size of opening to accommodate the thicknesses of insulation can be too narrow to accommodate a standard door width, too short to permit a full standard sized door, or too small to provide sufficient light at windows. The solution is to either omit insulation at the jambs, sills and lintel soffits, or to reduce the applied thicknesses at these surfaces. Commonly the wall insulation is 75mm to 100mm thick, and the reduced thicknesses are 25mm thick. The elimination of insulation at these points or the reduced thicknesses provide a thermal bridge.

2.3.7 Thermal break at party wall/external wall junctions where EWI not extended across to neighbouring property

For EWI, adjacent properties may not be in the same ownership. The external wall insulation cannot therefore be applied onto the neighbouring property without incurring trespass, party wall issues, etc. To avoid conflicts arising the EWI needs to be kept away from the centre-line of the party wall. This generally results in a thermal break at this area, see Figure 2-12.

Figure 2-12 Thermal break at party wall/external wall junctions between differently owned terraced properties

A compensatory measure for this could be internally insulating part of the party wall, taking insulation around the party wall/ external wall junction, but this was not applied in any of the properties surveyed. It is also noted that where the party wall and external walls are insulated the external wall of neighbouring properties will not benefit from the heat exchange between properties. A reduction in heat gained from the adjacent properties results in the wall/external wall junction becoming colder and can make uninsulated neighbouring property more susceptible to condensation at this junction. Thermal models have also shown this to be the case, as shown in section 5.4 and Figure 5-2.

2.3.8 Thermal breaks introduced at intermediate floor/wall junctions for IWI

Thermal breaks are introduced at intermediate floor/wall junctions at many first floors where IWI is applied, as is illustrated at Figure 2-13. The floor joists tend to span party wall to party wall, and the last joist adjacent to the external wall positioned with a gap of around 25-50mm from the external wall. The effect of this can be seen in the infra-red image in Figure 2-13, showing a cooler area at the floor edge.

Although a solid brick wall with a plaster finish is reasonably air-tight, where there is no plaster finish, the wall is not air-tight due to the small fissures, hairline cracks, and gaps in the brickwork mortar that exists in all masonry walls. There is not normally a plaster finish to the floor void at intermediary floors because the plasterwork is carried out when the floor boards are in place. Therefore for the finished property following the IWI intervention, there can be a breach in the airtight layers at each floor.

Some properties include a polythene moisture barrier wrapping the final joist adjacent to the external wall which may avoid a breach of airtightness at this position. However if the insulation between the polythene and the external brick is not sufficient, there is likely to be condensation on the timber side of the polythene, wetting the joist and encouraging softening and fungal attack.

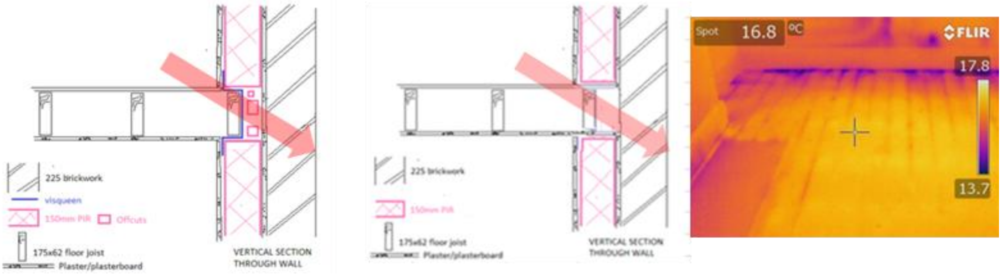

Figure 2-13 First floor/wall junction with IWI. There is likely to be a thermal bridge at floor level. The left hand example shows offcuts used between the joist and wall, although this is not always present, and if provided is unlikely to provide a continual effective insulating layer. The visqueen in the left hand example may avoid a breach of airtightness but may encourage condensation on the joist

Some contractors have avoided the risk of these types of thermal break by removing the floorboards and joists closest to the external wall, continuing the IWI in a straight line down the wall at the intermediate floor positions and replacing the floor joists further away from the external wall. This treatment was carefully conducted at one back-to-back property and one detached nineteenth century stone built house. This treatment cannot be undertaken where the floor joists are supported by the external wall, for example spanning from the front to rear walls in a terrace house, to the gable of a terrace, or to an external wall in a detached or semi.

2.3.9 External walls concealed behind bathroom and kitchen fittings

Two issues were noted following investigation into these concealed parts. There is no indication that there is any intention to omit works, but due to the numbers of professions involved at this point, works can get omitted or indeed completed but then adversely affected by follow-on trades.

Air gaps are introduced around service entries through external walls. As the service entries tend to be concealed behind kitchen units, bath panels and floor voids, it is not always noted that gaps around pipes and service entries, as they protrude through the external wall, have not been sealed. These gaps result in the loss of heated air and allow for the entry of cold air, see example at Figure 2-14.

Secondly where the property has IWI, the parts of walls behind bathroom and kitchen fittings are not always insulated, creating large thermal breaks. Where these two aspects are present in the same properties the adverse effects were exacerbated.

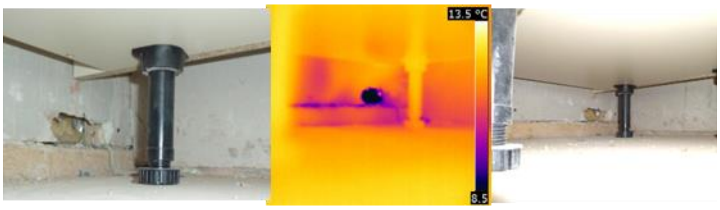

Figure 2-14 Void below kitchen cupboard. Hole made through plasterboard and airtight layer exposing IWI, reducing airtightness and inducing thermal bypass

2.3.10 Chimney flues

The chimney flues in the properties surveyed were treated differently but each treatment brought its own challenges which were not resolved. These are shown diagrammatically in Figure 2-15. The ground floor flue is shown blocked off in the room and capped off at the chimney. This has been known for many years to result in a lack of ventilation to flue, increased dampness in flue, and risks of fungal attack to the timbers and of sulphate attack to the mortar joints, which can destabilise the chimney. The first floor flue has been finished with an airgrate in the room and a ventilated cap at the top on the chimney. This permits flue ventilation, reducing the risk of fungal and sulphate attack, but bypasses any applied airtight layer, permitting the loss of heated air through stack effect and natural ventilation up the chimney flue and the entrance of cooler air into the room, creating draughts. The flue on the second floor has had a partition wall built in front of it, sealed at the floor, ceiling and wall junctions but allowing ventilation into the floor voids. This permits some flue ventilation, reducing the risk of fungal and sulphate attack, but also permits ventilation through the floor boards thus bypassing the applied airtight seals and creates draughts. This latter solution was applied in one of the intensively investigated properties and the lack of integrity in the air tight layer produced contributed to a larger than expected air infiltration following refurbishment.

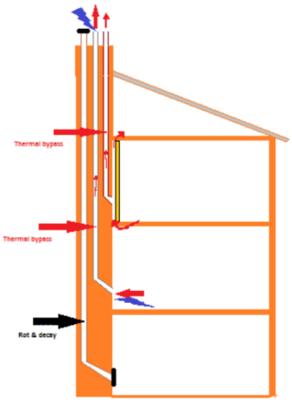

Figure 2-15 Effects of different flue treatments

2.3.11 Lack of associated improvement works

Particularly for the intervention of external wall insulation, it was found that there was a lack of associated simple or more complicated improvement works so that new problems were introduced. Some of these have been described in the sections above. One common example is that thermal bridges have been introduced where ground floors have not been insulated. Secondly where roof eaves and rainwater good are not amended thermal bridges at sensitive eaves level have been introduced and there will be a risk of condensation and likely future mould issues.

Where the upper floors sit partially in the roof void and, or where there are sloping ceilings, where the plasterboard or lath and plaster finish was applied (at construction) directly onto the roof rafters' lower sections, no attempts were seen to provide insulation to these slopes, even where the horizontal roof void insulation had been checked.

It was noted that roof void horizontal insulation was usually reported as having been checked prior to works. Where the depth at the access point was adequate for required standards, no further insulation was provided. However there was a lack of evidence that more detailed investigation was carried out in the void, as insulation was seen to be poorly laid in some properties, for example, not taken to edges against gable walls, party walls or eaves. In one property, there had been some repair works to a ceiling, some 2m^2 of the insulation moved aside and not replaced.

Insulation to the roofs to lean-to porches etc. is not necessarily part of upgrade works. Insulation to the main void roof void is usually a simple matter but insulation to flat roofed and lean-to attachments is more complicated especially as these roof areas do not usually have access. There may be some insulation in these areas provided at construction, but not to current standards. Improvement to current standards is not easily achieved without complete roof replacement. These areas often form part of the internal heated floor space, often connecting directly to the stairway, thus lack of insulation to an entrance hall roof permits heat loss throughout the house.

One effect of EWI and IWI has often been a decrease in draughts, particularly where there has been careful sealing around windows openings. Additionally, air grates built into walls for providing combustion air (no longer required) to old boilers or solid fuel fires were seen to be sealed during the works and then covered with the insulation. The properties can be more airtight. A downside of this was seen to be where there has been no replacement of the older type "replacement windows" which do not have trickle vents or accessible opening lights. The draughts supplied fresh air into the properties and allowed for air changes near to current standards. Once sealed, and without provision to introduce controlled fresh air into the home, there can be a poorer standard of fresh air provision which can result in increased condensation, noticeable to the occupants on windows and sills. This was particularly noticeable for occupants who did not care to open windows, for security or other reasons, or who were unable to reach higher level opening lights due to disabilities or due to the positioning of kitchen or bathroom fittings. Extractor fans in kitchens and bathrooms were not always provided and these properties tended to suffer from condensation and mould particularly in bathrooms. See also the unintended consequences of improved air tightness described in the chapter on airtightness, section 3.3.1.

2.4 Recommendations from surveys

General conclusions and recommendations:

- Undertake initial survey to determine the design challenges for the building(s)
- All intervention design will create own problems/consequences – find and resolve
- Take holistic view for the design – piecemeal interventions likely to result in piecemeal problems
- Be open to additional works – eg dpc provision, repointing, repairing gutters/downpipes, moving rainwater goods/drains, lowering ground levels, relaying roof void insulation, provision of extract fans into kitchens/bathrooms.

Condition of external walls:

- 51% of the properties surveyed had some higher levels of dampness but there was little evidence of that the condition of the external walls or challenge of penetrating dampness from any sources was routinely considered during the design period
- Little evidence was seen that current knowledge of insulating damp walls is being considered
- The cause and effect of dampness need resolution as part of the design

Insulation to roofs:

- Lack of attention in roof void to ensure sufficient insulation was laid at eaves
- Difficulties for design at sloping soffits requires resolution
- Omission of insulation to bow and bay windows, flat roofs and roofs without current access.
- Lack of attention to maintaining ventilation to roof voids treated with increased insulation
- Lack of attention to placing insulation, or replacing insulation and air barriers following later repair, M&E, plumbing works etc.

Obvious thermal bridges designed into EWI:

- Eaves: extensive thermal bridges seen at eaves where extending the roof, altering the gutters and rainwater collection arrangements were not being carried out

- Ground floor: starting EWI at or even above level of finished surface of ground floor
- Cut-outs in EWI for protrusions (e.g. pipes, garden walls, meter boxes)
- Lack of provision at bin stores/passageways/etc.

2.4.1 Surveying References

ASHRAE. (2013). Standard 55-2013 -- Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, Georgia, USA.

RICS. (2013). Surveys of residential property. 3rd edition. RICS Professional Guidance. RICS, London, UK.

3 Air-tightness tests

3.1 Overview of the blower door test

The airtightness, or their infiltration rate, is a measure of the uncontrolled ventilation rate of a dwelling. Together with purpose-provided ventilation this establishes the ventilation rate of the building fabric and how much heat is lost due to air exchange with the external environment. Heat loss through ventilation can have a major influence on energy efficiency; if the airtightness of a dwelling is not addressed during the refurbishment process the proportion of the dwelling's total heat loss attributable to ventilation heat loss can increase dramatically as other heat loss mechanisms are reduced[2].

Performing a blower door test is the approved method for ascertaining the airtightness of a dwelling in the Building Regulations 2010 Approved Document L1A (for new-build dwellings), Approved Document L1B (for existing dwellings) does not specify an airtightness test methodology only stating that "reasonable provision should be made to reduce unwanted air leakage through new envelope parts" (NBS, 2010a, NBS, 2010c).

The tests undertaken in this project were done in compliance with the approved procedure for new-build dwellings provided by the Air Tightness Testing and Measurement Association, Technical Standard L1A, Measuring Air Permeability of Building Envelopes (Dwellings) (ATTMA, 2010). Tests were conducted using an Energy Conservatory Minneapolis Series 3 blower door system, and the results reported (unless stated otherwise) are the mean value of both pressurisation and depressurisation tests. Where leakage detection was also performed to identify points of air leakage and infiltration pathways, this was carried out using handheld smoke puffers under dwelling pressurisation and by thermography under depressurisation. An induced pressure of +/- 50 Pa was used throughout this investigation when conducting leakage detection.

3.2 Results of retrofit air tightness improvements

The details of each blower door test undertaken in this research are shown in Appendix B, though the results are summarised here in Table 3-1 which shows as might be expected a reduction in infiltration rate was achieved in all the dwellings where interventions took place and for which there are before and after data. However, the range of improvement achieved is also very large suggesting there might not be a *typical* improvement level. It is important to note that there were no air tightness tests performed on dwellings which only had EWI and so its effect is not discussed here.

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[2] http://www.leedsbeckett.ac.uk/teaching/vsite/low_carbon_housing/airtightness/introduction/index.htm

Table 3-1 Improvement in dwelling infiltration

Dwelling	Primary Intervention	Mean before $m^3/(h.m^2)$@50Pa	Mean after $m^3/(h.m^2)$@50Pa	Improvement
C-01	IWI and whole house	16.8	6.53	61%
C-02	IWI and whole house	24.1	20.2	8%
C-03	PWI	16.5	14.9	10%
I-02	IWI	19.2	12.1	37%
I-03	IWI	-	4.7	-
I-04	IWI	27.9	20.2	28%
I-05	IWI	-	13.0	-
I-06	IWI	-	11.9	-
I-07	IWI	11.4	10.5	8%
I-08	IWI and EWI	12.4	10.3	17%
I-09	Edufoam	17.7	-	-
I-10	Edufoam	12.5	8.3	34%
I-13	IWI	-	10.8	-
I-14	IWI	-	6.9	-
I-15	Edufoam	10.5	-	-
E-42	DIY sealing	16.62	12.73	23%
			Average improvement	*25%*

The 34% improvement in airtight performance of I-10 resulted from a closed-cell foam being injected into the empty wall cavities, the foam formed a continuous airtight barrier around the dwelling. However, the other retrofit solutions measured here allowed internally applied insulation to increase the airtight performance of areas of the external envelope, but did not always address junctions, penetrations and openings and did not fully consider how the air barrier would be made continuous around these details.

In dwellings C-01 and E-42 the air tightness of the dwellings was a particularly important part of the retrofit and as a result the improvements achieved were high, yet incidental improvements in air tightness were also achieved as a consequence of all the other retrofit although the improvement factor varied greatly.

This is an interesting observation since currently when predicting the energy performance of insulation, the additional benefit that increased air tightness may provide is not considered and so one might assume that some predictions may currently underestimate performance of retrofits. However, research studies into the performance gap, as well as the NEED analysis show that actually predictions even without the benefit of air tightness still overestimate the predicted savings of insulation installations. Traditionally, in-use factors have addressed this problem, yet it may be that the performance gap could be larger than is currently suggested when savings from air tightness are also considered.

Figure 3-1 illustrates the findings from the air tightness tests in this study; a shift to the left (reduction in air leakage) can be observed for those properties that have had a retrofit. It is important to note that in this data there are dwellings for which there was only before or after air tests performed so this is not a measure of improvement, though generally the trend identifies that the *after* dwellings are more air tight but also that this is not always the case.

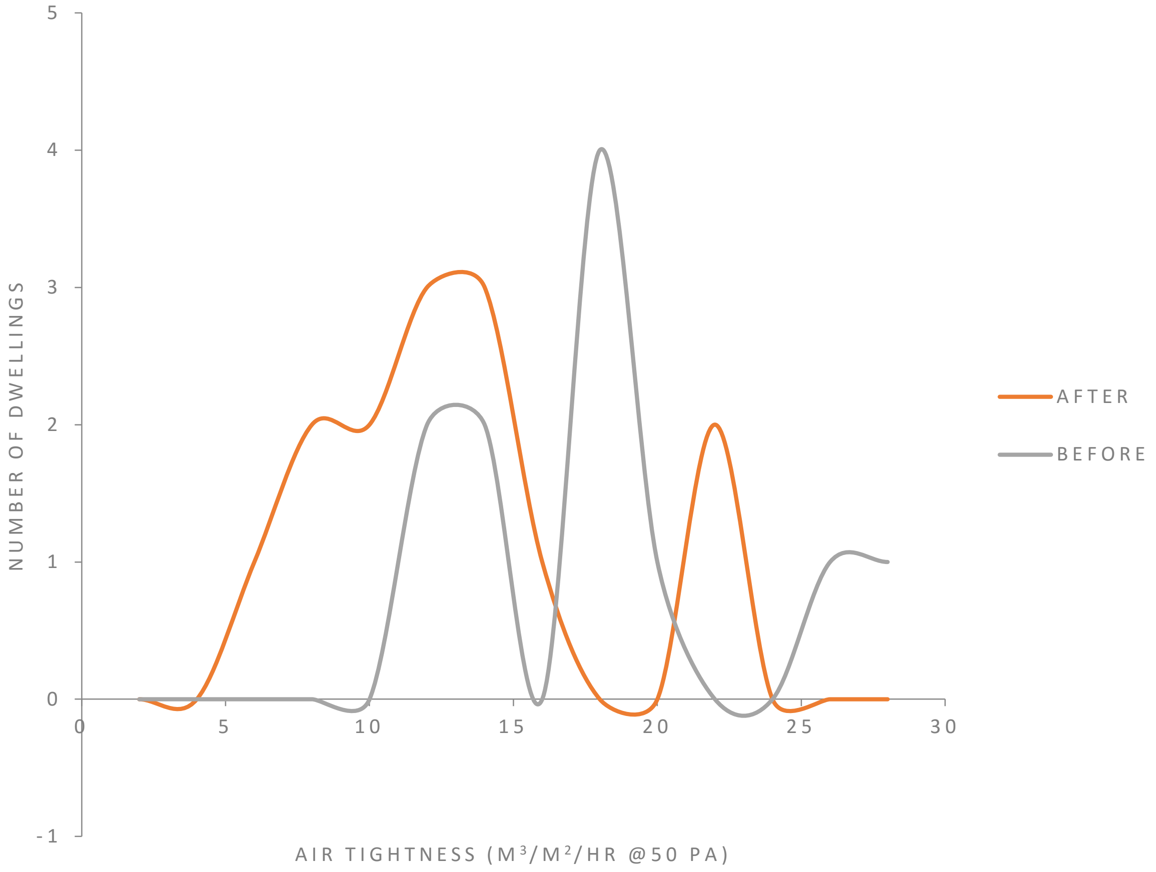

Figure 3-1 General dwelling air tightness

When we compare the results of this finding to the Innovate UK's Retrofit for the Future air tightness data in Figure 3-2 we see similar trends whereby refurbishment schemes which include the application of insulation have also registered improved air tightness in these dwellings.

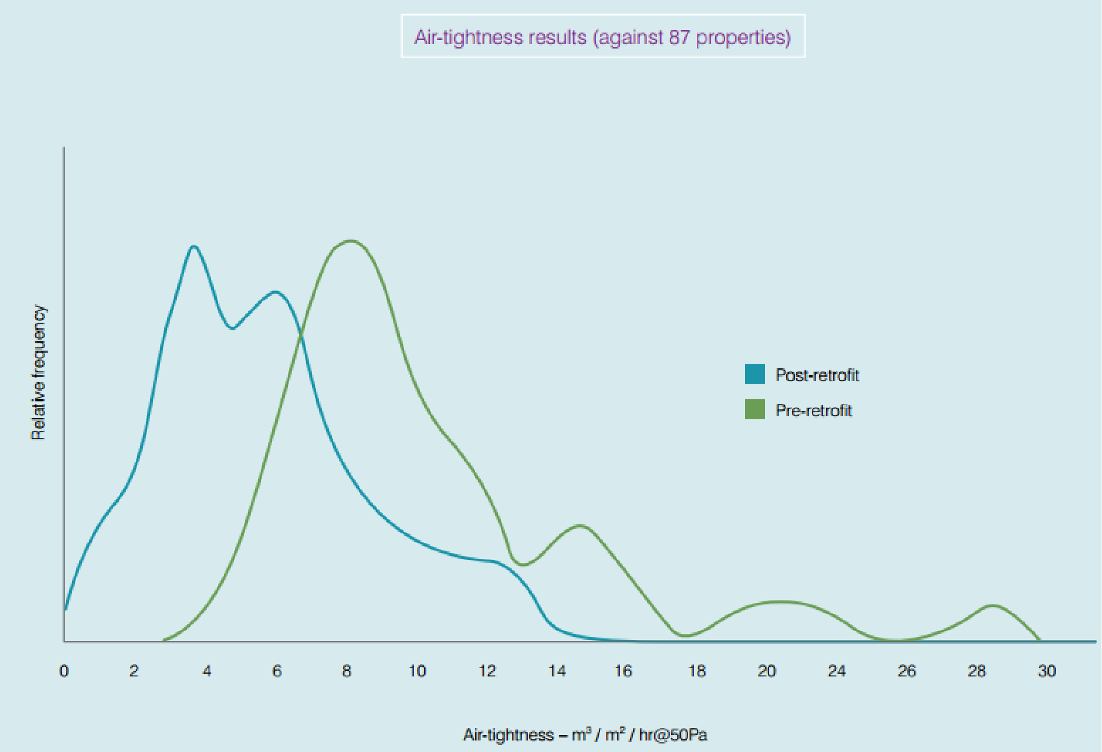

Figure 3-2 Retrofit for the Future air tightness results (Innovate UK, 2016b)

Although some improvements are observed, it is also worth noting that it is not always those dwellings that are the draughtiest that benefit the most because the quality and scope of the retrofit, in addition to the dwelling's original draughtiness, are both key determinants of the improvement observed. One example of this is to compare dwellings C-01 and C-02.

In C-01 a conscientious effort was made by the installers regarding the air barrier as this was part of a whole house retrofit delivered by a local housing charity. The retrofit design included details of what comprised the primary barrier, allowing discontinuities in it to be addressed and breaches to be repaired. By contrast C-02 was a very similar dwelling with a very similar whole house retrofit; however, the work was undertaken by sub-contractors and there was far less emphasis placed on the importance of the air barrier. As a result, although the starting air tightness values of the dwellings were not dramatically different, the after results for C-02 showed it was not as successful and resulted in a refurbished house that still has an air infiltration rate twice that of the maximum allowed in Part L for new dwellings. The lack of attention to detail is likely to significantly undermine the success of the retrofit and is a theme explored further in Section 4.

Similarly, I-02 and I-03 were neighbouring dwellings where 2 different approaches were taken to the whole house retrofit. From similar starting positions the final airtight performance of the

2 dwellings varied considerably. The sub-contractors refurbishing I-02 were highly conscious of time and labour costs, so utilised solutions which minimised these; for the local housing charity refurbishing I-03 the main concern was material costs and developed alternative solutions accordingly. Figure 3-3 illustrates these alternative approaches to the same detail, the suspended timber ground floor above the cellar. The contractors fitted insulation to the floor and a new airtight cellar ceiling, the local housing charity removed the existing cellar ceiling and sealed around the floorboards and joists before installing the floor insulation. The result was that the local housing charity virtually eliminated infiltration through the ground floor and attained a final air permeability result below 5 m^3/(h.m^2) @ 50Pa, the sub-contractor retrofit left infiltration paths through ground floor around the joists into the “solid” walls and an air permeability of over 12 m^3/(h.m^2)@ 50Pa.

Figure 3-3 Dwellings I-02 & I-03, and the different treatment of the suspended timber ground floor, views from the cellar; top – contractor retrofit, bottom – local housing charity retrofit prior to insulation installation

An indication of the importance of the attention to detail in the air tightness of refurbishments is indicated in Figure 3-4 where the three most improved performing homes C-01, I-03 and I-14 were all refurbishments where the whole house was considered in the retrofit and the installer was either the building owner or had an interest in the project success and so the work was not subcontracted out. It is also worth considering that in ten of the sixteen dwellings tested after the retrofit still had air tightness levels worse than the maximum allowed under building regulations for new dwellings (shown in Figure 3-4 as a dashed green line) indicating that there may be much more scope for improving the thermal performance of dwellings through a targeting of air tightness improvements.

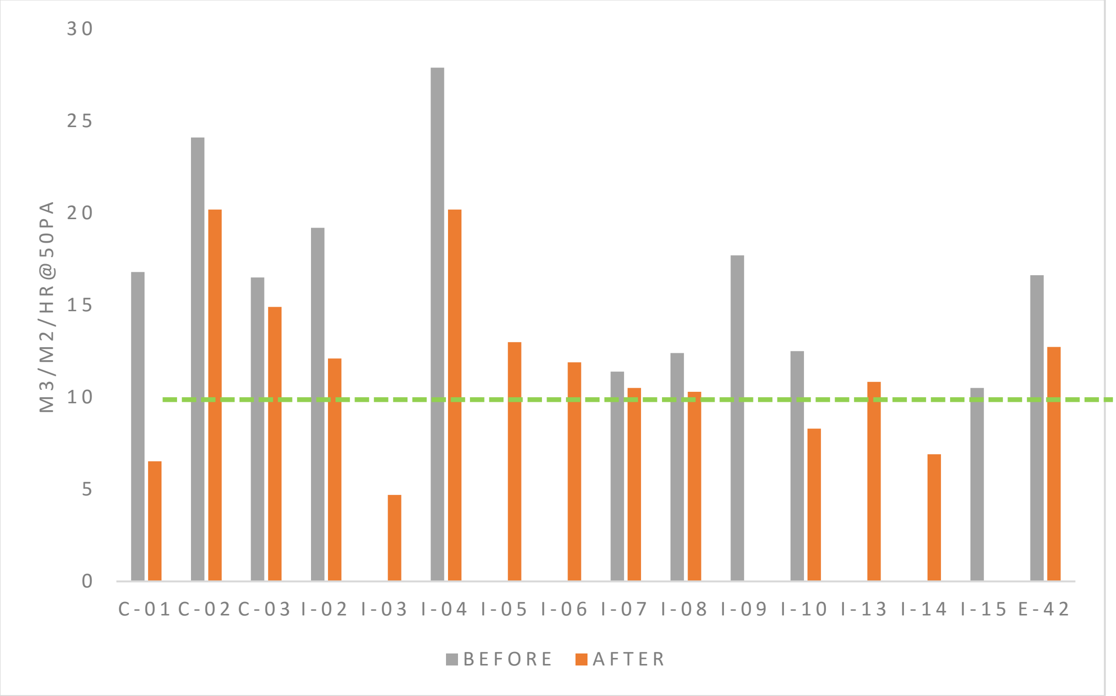

Figure 3-4 Overview of specific air tightness tests

3.3 Common causes of poor air tightness

In a number of solid-walled dwellings investigated the internal wet-plaster finish was removed due to its poor condition, and a new internal wall lining of either plasterboard or insulated plasterboard was applied using dabs of adhesive to fix the new boards to the un-finished masonry wall. Figure 3-5 shows how the “inner leaf” of a solid wall can allow air exchange between the “finger cavity” of the solid wall and the dwelling interior through unfilled perpends and bedding layers between the bricks. The old internal plaster finish provided an effective air barrier, removing this (as in Figure 3-6) creates additional air leakage paths that were not present prior to refurbishment. Figure 3-7 illustrates these new post-retrofit air leakage paths, with air entering from the solid wall finger-cavity through gaps in the inner leaf and travelling around the plasterboard adhesive dabs behind the plasterboard on the internal wall.

Figure 3-5 The difference in quality of brickwork between inner and outer leaf of a solid wall and the finger cavity between the them

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Figure 3-6 Dwelling C-02 prior to application of IWI insulated plasterboard on the external wall and plasterboard on the internal wall.

Figure 3-7 Dwelling C-02 under depressurisation following refurbishment.

Direct air leakage paths existed in all the dwellings tested and are the easiest to detect and remedy. These direct paths are where air infiltration or exfiltration occurs directly between the living space and outside. Examples include gaps around doors and windows, service penetrations, loft hatches and suspended timber ground floors; many of these were addressed to varying degrees during the renovation work. However, it appeared to be the indirect air leakage paths that were not adequately addressed at many of the sites examined. Indirect air leakage involves air moving from the living space into one of many interconnected voids around the dwelling and then exiting at a location some distance removed from the internal point of air leakage; Figure 3-7 illustrates an example of this. These voids include service voids, voids under baths/showers, voids behind kitchen units, intermediate floor voids, partition wall voids and voids behind plasterboard dry linings fitted on battens or dabs of adhesive. Under dwelling depressurisation, it was common to observe floor coverings ballooning up as air entered (often around intermediate floor joists) and spread around the dwelling, although it was rarely possible to identify exactly where that air was entering the property.

3.3.1 Unintended consequences of improved air tightness

The increasing of air tightness in dwellings is a potential concern for some retrofit projects due to the unintended consequences of sealing up buildings too tightly, to the point where inadequate ventilation supplied to the dwelling becomes a risk. This affects indoor air quality and occupant health as well as encouraging the build-up of moisture, condensation, damp and mould growth in dwellings.

A useful guide to the degree of risk of unintended consequences is to consider that mechanical ventilation is only required in homes where the airtightness is likely to be below 0.5 to 1ach (CIBSE, 2001). The Building Regulations state that for new-build dwellings with an as-built air permeability of ≤3 $m^3/(h.m^2)$@50Pa natural ventilation alone will not provide the necessary fresh air input and stale air extraction required for both occupant and building health (NBS, 2010b). This study has shown however that the post intervention infiltration rates are still relatively high, ranging from 4.8 to over 20 $m^3/(h.m^2)$ @50Pa, and so it may be assumed (if no existing moisture issues are present) it is unlikely that these retrofit would cause unintended problems with moisture as natural ventilation is deemed sufficient under normal circumstances.

The natural air movement and pathways within a dwelling are driven by pressure differences between the conditioned space and the external environment. The main drivers for natural air exchange are wind effect and stack effect. Wind effect denotes that infiltration will be encouraged on the windward side(s) of a dwelling, whilst exfiltration will be intensified on the leeward side(s). Stack effect results from the external air pressures being greater at ground level than at increased heights, so the ground floor becomes an infiltration zone and the top floor ceiling an exfiltration zone; the level at which it changes from one to the other can vary due to a range of factors. With many of the test dwellings included in this study having basements or being back-to-back form this can have consequences. The basements tend to be unheated and quite damp, but provide the main source of natural ventilation (through stack effect) into the dwellings through and around the suspended timber ground floor above. If this air is cool and humid it is not so problematic, because when it enters the living space it warms up and its relative humidity drops considerably; however, if the residents heat their basement, the air entering the conditioned space becomes warm and humid, carrying substantially more moisture into the house. In back-to-back houses with basements this problem is amplified, as there is no wind-driven through ventilation as the houses only have the one external façade.

A further issue associated with retrofitting of existing buildings is how this can be done without removing the occupants. Regarding airtightness this work would indicate that IWI is unlikely to provide a successful solution when adopting a staged approach to refurbishment due to the detailing issues in achieving a continuous air and thermal barrier. The only truly successful IWI retrofits observed were in whole-house refurbishments, which were only possible in unoccupied dwellings. Staged approaches to IWI were observed to leave floor voids, areas behind kitchen units and areas behind bathroom fixings untreated, both for thermal upgrades and for airtightness; and as bathrooms and kitchen are areas where warm moist air is most prevalent these are also the areas most prone to condensation and mould propagation.

3.3.2 Energy efficiency and improved air tightness

It is difficult to directly correlate fuel bill savings to air tightness levels. The fact that air tightness may be improved as a consequence of installing insulation is an interesting finding and supports current thinking. To support the concept that mass application of air tightness in dwellings may be an appropriate energy efficiency solution in itself more research is needed. It was not possible to incorporate energy monitoring into all these homes as often they had unsuitable gas meters or else there was insufficient before monitoring time available. However dwelling E-42 did have in-use monitoring equipment before and after the improvements were made to airtightness and these results are discussed in Chapter 7.

SAP 2012 version 9.92 (BRE, 2012) Section 2 quantifies ventilation rate via a number of inputs, usually the most significant of which is the fabric air permeability. This ventilation rate is then used to estimate a value for the dwelling heat loss through ventilation. This calculated value will often remain relatively constant when a dwelling undergoes retrofit; so as the conductive heat loss through the fabric is reduced by utilising additional insulation, the proportion of the total heat loss of the dwelling due to ventilation (both intended and unintended) can increase dramatically. If accurate predictions of the retrofit's planed improvement are needed (for example in funding schemes like the Green Deal), it may be necessary that an air tightness test is undertaken before and after the retrofit to improve the accuracy of EPCs.

3.3.3 Future ventilation issues to be researched

The project has raised several research questions that might influence future studies and existing findings. For example, the blower door tests used here and elsewhere rely on a relatively historical assumption that the air tightness testing under pressurised and de pressurised conditions can be converted to the actual every day fabric air permeability of a dwelling. This assumption could be challenged if it were possible to compare the blower door test method in a large number of homes with the alternative tracer gas method of determining background ventilation rates.

It might also be interesting to investigate if there could be a way of linking in-use data on tracer gasses to smart meters and smart whole house heating controllers to provide a basic infiltration rate when undertaking energy payback calculations and providing occupant feedback.

Such a project may also be used to understand if the current “n/20” approximation used in the air tightness calculations is always applicable. In addition, if the sample size were large enough it may also be interesting to challenge the assumed default airtightness levels assumed in SAP. There may be scope for providing different defaults for different building archetypes or indeed for updating the universal default used when no air tightness test is undertaken. This would be likely to improve the accuracy of EPC scores and provide more useful information top occupants in terms of their anticipated energy use but also prioritising retrofit measures.

If airtightness of dwellings is to be researched further it will be necessary to also incorporate an element for unintended consequences since changing the ventilation rates in dwellings can cause significant adjustments in moisture build up.

3.3.4 Summary of findings from air tightness investigations

There were a variety of observations made in the individual test reports presented in Appendix B.

- Air tightness will incidentally be improved in most IWI and cavity wall fill retrofits;
- Problem zones include direct loss to the outside (e.g. around doors and windows, service penetrations, loft hatches and suspended timber ground floors) and more easily missed indirect losses where air moves from living space via interconnected voids and out at *hidden* locations;
- Where an explicit air barrier was detailed as part of the retrofit design process, the increase in airtightness of the refurbished dwellings showed the greatest improvements;
- There is a lack of understanding of airtightness and ventilation within a large proportion of the retrofit industry, and a misunderstanding of its importance to the success of projects;
- As airtightness was not a specific Green Deal measure it was only addressed by those who had previously recognised its impact on retrofits; and
- A staged approach to IWI is inadvisable due to the risks surrounding untreated areas, it is much more likely to be successful when applied as a whole-house solution in an unoccupied dwelling.

3.3.5 Air tightness references

ATTMA 2010. Technical Standard L1A, Measuring Air Permeability of Building Envelopes (Dwellings) In: ASSOCIATION, A. T. T. A. M. (ed.). Air Tightness Testing and Measurement Association.

BRE 2012. The Government’s Standard Assessment Procedure for Energy Rating of Dwellings 2012 edition. Watford: BRE.

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4 Co-heating tests

4.1 Overview of test

The co-heating test is a protocol for attempting to measure the as built heat loss coefficient (HLC) of a building. This is an important metric since it quantifies the actual energy efficiency of the dwelling excluding (as far as possible) the complications of the occupant or interactions with environmental conditions. This means the impact on thermal performance of individual retrofit improvements can be isolated and quantified, to a degree. Three dwellings were identified as suitable for performing a co-heating test in this research which are described in Section 4.3.

4.1.1 Co-heating test design

A two stage test programme was designed to measure the improvement in thermal performance resulting from the full-retrofit, the test stages were designated as:

- Before (pre-retrofit)
- After (post-retrofit)

The following measurements of thermal performance were taken at each stage of the test programme to assess the effectiveness of the retrofit:

- *In situ* U-values quantify the thermal transmission of test house’s thermal elements.
- Heat loss coefficient (HLC) is the whole house heat loss of the test house.
- Airtightness measurement from which the background ventilation rate of the test house can be derived.

The measurements obtained in the pre-retrofit test stage formed the baseline values of thermal performance from which the effectiveness of the retrofit measures were quantified.

4.1.2 Co-heating test Methods

External environment monitoring

External air temperature, relative humidity, wind speed and wind direction was measured using a Vaisala WXT520 weather transmitter located in the garden of the test house. Solar insolation was measured using a south facing vertically orientated Kipp and Zonen CMP 3 pyranometer. External environmental and temperature measurements were logged at ten minute intervals using an Eltek Squirrel RX250AL data logger. Missing data were corrected using linear interpolation.

Internal environment monitoring

Internal environmental measurements (air temperature, RH, CO2 concentration) were obtained using an Eltek monitoring system which recorded measurements at one minute intervals to an Eltek Squirrel RX250AL data logger. Missing data were corrected using linear interpolation.

- Internal air temperatures were measured using PT100 RTD temperature sensors (± 0.1 K).
- Internal surface and cavity temperatures were obtained using Type K thermocouples (± 1 K).

Heat Loss Coefficient

Estimates of the HLC for the test house at each test stage were obtained from co heating tests undertaken in accordance with the protocol developed by Leeds Beckett University (Johnston, 2013).

- The fuzzy logic thermostatic temperature controls were set to ensure the electric resistance heaters maintained a stable internal air temperature.
- Electrical power input to the test dwelling was measured using Elster A100C energy meter which provided one pulse per Wh electrical energy delivered (± 1%).

In situ U-value measurements

In situ U-value measurements were undertaken during the coheating tests in accordance with ISO 9869 (ISO, 2014).

- *In situ* measurements of heat flux density, from which *in situ* U-values are derived, were obtained using Hukseflux HFP01 heat flux plates (HFPs. The voltage induced by the HFPs was recorded at one minute intervals by Thermo Fisher Scientific dataTaker DT80 data loggers.
- HFPs were positioned in locations considered to be representative of the whole element, as well as other locations of interest to the research team.
- HFP positioning was informed by the use of a thermographic survey using a Flir B620 thermal imaging camera.
- HFPs were affixed to the surface of each element using thermal compound and adhesive tape.
- The elevated and stable internal temperatures experienced during the coheating test are conducive to obtaining accurate measures *in situ* U-values. Air circulation fans were used during the coheating test to ensure even distribution of temperatures throughout the test dwelling. However, care was taken to ensure that HFPs were not unduly influenced by excessive air movement by positioning fans in such a way that air was not blown directly on to the HFPs.

- 24-hour U-values reported for all elements are for 24-hour time periods commencing at 06:00.
- To compensate for thermal inertia and storage effects, U-values were calculated using the Average Method contained within ISO 9869; which is a cumulative moving average of measured heat flux and ΔT (ISO, 2014).
- Unless otherwise stated the uncertainty associated with *in situ* U-values measured at the location of each HFP is 10%. It must be noted that *in situ* U-values presented may not be representative of the thermal element as a whole, as measurement of heat flux was obtained from only a small proportion of the total party wall surface area.

Background ventilation rate

The background ventilation rate of the test house was derived from the fan pressurisation test air leakage rate at 50 pascals (n_{50}) using the $n_{50}/20$ rule (Sherman, 1987). The derivation includes the correction factor for dwelling shelter factor which is contained within the SAP 2012 methodology (BRE, 2012). The fan pressurisation tests were undertaken using a blower door in accordance with ATTMA L1 (ATTMA, 2010). The uncertainty associated with this method is highly dependent upon the environmental conditions present during the test.

4.2 Co-heating test dwellings

The test requires a minimum of two weeks of unoccupied time before and two weeks after the retrofit for the measurements to take place. Finding suitable dwellings is therefore relatively difficult since not only were voids relatively rare, RSLs with housing waiting lists were often not able to justify leaving a let table property vacant for two weeks.

However, three buildings were identified as suitable for a co-heating test as part of this project; C-01, C-02, and C-03 as described in Table 4-1. A design review for dwelling C-01 was also commissioned as part of the project and this can be viewed in Appendix C.

Table 4-1 Dwellings undergoing co heating tests

Dwelling	House type	Intervention 1	Intervention 2	Intervention 3
C-01	Solid brick, back to back, 1900s terrace with basement	IWI (150 mm PIR λ 0.022 with 12.5 mm plasterboard λ 0.19)	Loft insulation (Ridge soffit 150 mm PIR λ 0.022; Sloping ceiling 100 mm PIR λ 0.022; Knee wall 150 mm PIR λ 0.022)	Floor insulation (175 mm glass mineral wool λ 0.04 between joists. Underside of floor sealed with 12.5 mm plasterboard λ 0.19)
C-02	Solid brick, back to back, 1900s terrace with basement	IWI 72.5mm (PIR thermal laminate plasterboard)	Floor insulation (150 mm mineral wool assumed λ 0.04)	Replacement front door
C-03	Filled cavity Brick, mid terrace, 1950s	Party wall insulation and capping with blown mineral wool		

4.3 Co-heating test results summary

The detailed description of the test method and data analysis can be seen in Appendix C, E, and F. The results of the tests are summarised here in Table 4-2.

Table 4-2 Overview of retrofit reduction in HLC

Dwelling	HLC before intervention (W/K)	HLC after intervention (W/K)	Improvement in HLC (%)
C-01	138.2 (± 2.8)	60.9 (± 1.2)	56%
C-02	135.3 (± 2.5)	101.6 (± 3.8)	25%
C-03	180.2 (± 9.2)	166.4 (± 4.8)	8%

In each case the retrofit has led to an improvement in the HLC of the dwelling so were, to some degree, a success. C-01 and C-02 were both solid wall properties having IWI installed and so, as may be expected, they each achieved a greater reduction in HLC than C-03, which had cavity walls and only had a party wall filled. However, since these were similar dwellings receiving similar retrofits, the difference in reduction between C-01 and C-02 is noteworthy.

C-01 was undertaken by a housing charity that invests in improving the skills of local homeless people by involving them in whole house retrofits. The retrofit for C-02, although several measures were included did not have a whole house approach and the work was subcontracted to local companies on a job by job basis. The installers' attitudes to the retrofits was not formally investigated as part of the project and while the disparity measured cannot be wholly attributed to this difference in installer approach and design, the site observations made by researchers indicated that this had a substantial bearing on the retrofit outcomes.

4.3.1 Fabric versus ventilation heat loss

As described the dwelling HLC is composed of ventilation and fabric losses. A retrofit will affect both these so it is useful to disaggregate the improvements achieved.

Table 4-3 shows the improvement made by the three retrofits to ventilation rates due to the insulation filling air cavities and therefore sealing thermal bypasses. The first observation is that the dwellings have particularly poor levels of airtightness to begin with compared to the Building Regulations maximum allowable limit of 10 ach @ 50pa.

C-01 has made a substantial improvement, since air tightness was an integral part of the whole house retrofit. Conversely C-02 and C-03 were more conventional retrofits in that they focussed on only one measure and the improvement in air tightness they have achieved may in some way be considered incidental and perhaps more representative of the majority of retrofits that take place.

Table 4-3 Ventilation heat loss improvement

Dwelling	Before ventilation rate (ACH @ 50 Pa)	After ventilation rate (ACH @ 50 Pa)	Before heat loss (W/K)	After heat loss (W/K)	Improvement (W/K)	Percentage Improvement
C-01	20.85	7.99	38.9	14.9	24.0	62%
C-02	30.19	26.36	56	48.9	7.1	13%
C-03	17.81	16.11	40.2	36.3	3.9	10%

Table 4-4 presents the fabric heat loss improvements made by the retrofits and it is interesting to note that the absolute improvement in HLC achieved by the ventilation reductions in C-01 were almost equal to the fabric improvements achieved by C-02 and substantially more than the fabric improvements achieved by C-03.

The measured wall U-value improvements were substantial although not equal to the calculated U-values that were aimed for, i.e. some performance gap existed. The negative U-value measured in C-03 for the party wall is due to the fact that once filled the party wall can act as a thermal store meaning heat was recorded being emitted back into the dwelling from the walls, so the U-value is effectively zero (this is more fully explained in Appendix F).

Insulating solid external walls is shown to offer substantially more potential to reduce heat loss than filling cavity party walls, although it is much more expensive to undertake. Data on costs of the retrofit were not recorded in this project and so the cost effectiveness of reducing energy consumption via each method is not known.

Table 4-4 Fabric heat loss improvement

Dwelling	Before U-value (W/m^2K)	After calculated U-value (W/m^2K)	After measured U-value (W/m^2K)	U-value performance gap (%)	Before heat loss (W/K)	After heat loss (W/K)	Improvement (W/K)	Percentage Improvement
C-1	2.08	0.14	0.17	21%	99.3	45.0	53.3	54%
C-2	1.57	0.29	0.31	7%	79.3	52.7	26.6	34%
C-3	0.3	n/a	-0.02	n/a	140.0	130.1	9.9	7%

The improvements observed in ventilation and fabric are shown as their relative impact on the HLC reductions in Figure 4-1. Ventilation improvements could be assumed to be able to responsible for between 20% and 30% of overall heat loss in a dwelling retrofit, depending on the priority given to the air barrier in the retrofit design.

However, the findings have shown that airtightness improvements could, in buildings which have particularly poor starting background ventilation rates, in retrofits that pay particular attention to air barriers, achieve a reduction in HLC of roughly equivalent in magnitude to fabric improvements achieved by IWI and far in excess of the improvements achieved by party wall cavity fill. This indicates that there may be value in further investigating airtightness reductions in achieving reductions in dwelling fuel bills.

Although data on costs of the retrofit were not recorded in this project, sealing dwellings is much cheaper than insulating them. It is an interesting finding therefore that ventilation improvements alone can contribute substantially to reducing heat losses. Investigating the relative cost effectiveness of ventilation versus fabric improvements would make for an interesting future study.

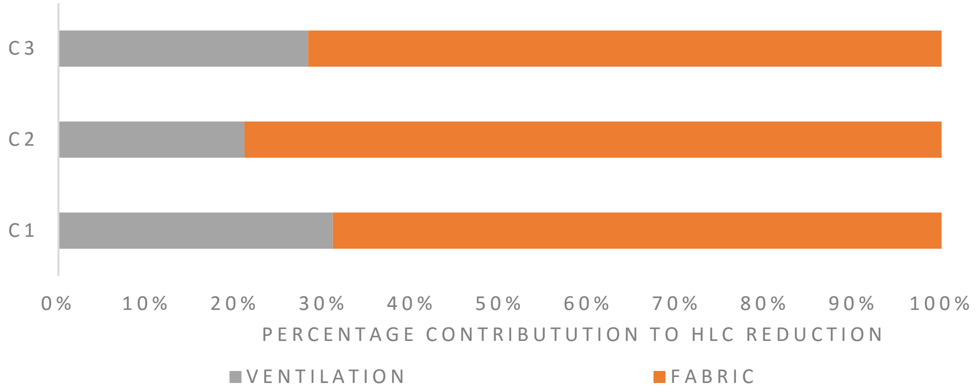

Figure 4-1 Contribution of ventilation and fabric on improvements in dwelling heat loss

4.4 Co-heating references

ATTMA 2010. Technical Standard L1A, Measuring Air Permeability of Building Envelopes (Dwellings) *In:* ASSOCIATION, A. T. T. A. M. (ed.). Air Tightness Testing and Measurement Association.

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5 Thermal bridging

5.1 Overview of thermal bridging calculations

This section presents the results of thermal bridging calculations that were undertaken to assess the performance of a selection of building fabric design details. These related to the renovation and thermal upgrading of brick built terrace properties constructed circa 1900 in Leeds. The design retrofitted the existing solid brickwork external walls with internal wall insulation (IWI). Junctions including ground floor, party wall/ground floor, party wall and masonry internal partition connecting to the external walls were thermally modelled to investigate the thermal performance of the designs. These junctions were selected because the designer considered them to present the greatest challenge when preparing designs for a scheme of thermal upgrading works.

5.2 Thermal bridging calculation method

Thermal bridging calculations were performed for 20 No. junctions to ascertain the linear thermal transmittance (Ψ-value or psi value) and temperature factor (f_{Rsi}) for each. The junctions comprised variations of the ground floor, party wall/ground floor, party wall and internal partition as identified in Table 5-1. Two thicknesses of 150 mm and 100 mm IWI where compared for each of the junction designs (see calculations in Appendix A).

The numerical modelling technique known as thermal modelling was employed to inform the thermal bridging calculations. All thermal modelling was undertaken using the Physibel TRISCO version 12.0w software (Physibel, 2010). The conventions given in BR 497 (Ward & Sanders, 2007) were followed where applicable and the use of any deviations from the conventions are described in this report. The equivalent thermal conductivities of air layers (cavities) were obtained from BS EN ISO 6946 (British Standards Institution (BSI), 2007) with the properties of airspaces calculated using the Kornicki Air Cavity Calculator (Kornicki, n.d.). Basement temperatures were predicted using version 2.03 of the Building Research Establishment (BRE) U-value calculator (BRE, 2011). The thermal conductivities (λ) of materials were sourced from manufacturers' literature where possible based on the project specification. In instances where these could not be obtained suitable values were sourced from BS EN 12524 (BSI, 2000) or from BR 443 (Anderson, 2006). The geometry of the thermally modelled junctions was based on the content of the design drawings and also from site observations.

5.3 Thermal bridging results

The results of the thermal bridging calculations are presented in tabulated format for each junction detail in Appendix A. A summary of the results are presented in Table 5-1 for ease of reference. The subscript number against some of the column headings refers to a particular side of a party wall. Values with a subscript one (e.g. Ψ_1) apply to the subject property side of the party wall and values with a subscript two (e.g. Ψ_2) apply to the adjoining property side.

Table 5-1 Summary of thermal bridging calculations

Junction	Ref	Ψ (or Ψ_1):	Ψ_2:	f_{Rsi} (or f_{Rsi1}):	f_{Rsi2}:
Ground Floor With Joist Parallel (50 mm) and 150 mm Wall Insulation	TB/01	0.016		0.917	
Ground Floor With Joist Parallel (40 mm) and 150 mm Wall Insulation	TB/02	0.015		0.918	
Ground Floor With Joist Parallel (50 mm) and 100 mm Wall Insulation	TB/03	0.022		0.901	
Ground Floor With Joist Parallel (40 mm) and 100 mm Wall Insulation	TB/04	0.021		0.902	
Ground Floor With Joist Parallel (50 mm) and 150 mm Insulation with Air Cavity	TB/20	0.016		0.918	
Party Wall 150 mm Insulation	TB/05	0.107		0.951	
Party Wall 150 mm Insulation with Air Cavity	TB/13	0.103		0.953	
Party Wall 100 mm Insulation	TB/06	0.115		0.943	
Party Wall 150 mm Insulation Single Side	TB/07	0.026	0.410	0.970	0.670
Party Wall 100 mm Insulation Single Side	TB/08	0.033	0.404	0.960	0.672
Party Wall 150 mm Insulation Full Return	TB/15	0.103		0.950	
Party Wall 150 mm Insulation No Return	TB/16	0.169		0.860	
Party Wall Uninsulated	TB/12	0.232		0.718	
Partition 150 mm Insulation	TB/09	0.097		0.954	
Partition 150 mm Insulation Single Sided Return	TB/14	0.158		0.967	0.856
Partition 150 mm Insulation with Air Cavity	TB/21	0.094		0.955	
Partition 100 mm Insulation	TB/10	0.095		0.945	
Party Wall/Ground Floor	TB/11	0.091		0.913	
Party Wall/Ground Floor Insulation Single Side	TB/17	0.034	-1.052	0.934	0.835
Party Wall/Ground Floor Uninsulated	TB/18	-2.211		0.841	
Party Wall/Ground Floor with Air Cavity	TB/19	0.088		0.913	

5.4 Thermal bridging findings

The current conventions (Ward & Sanders, 2007) treat party wall junctions with the external wall by calculating a Ψ-value for the whole junction and dividing this equally between the premises to each side of the party wall. However, there is currently no convention for the proportional assignment of Ψ-values where only a single dwelling in an attached arrangement is being thermally upgraded. The lack of a convention has implications for whole building energy use and carbon dioxide (CO_2) emissions calculations. An example would be where thermal bridging parameters could be input to an energy assessment for a conversion to take advantage of the improvements made upon the default y-value. In order to calculate Ψ-values for a thermally asymmetric junction a procedure had to be devised. The approach taken was to setup the thermal models with independent boundary conditions to each side of the party walls so that the heat flow (Q) from each occupancy could be individually ascertained. The Qs were then converted into thermal coupling coefficients (L^{2D}) between the internal (T_i) and external (T_e) environments for each premises. The modelling U-value (U_w) for the external wall flanking element multiplied by its length (ℓ_w) was then subtracted from the respective L^{2D} to calculate Ψ-values for each side.

Equation 1 and Equation 2 show the procedure implemented. The same approach was taken with the ground floor/party wall junctions but with the term $U_w \cdot \ell_w$ in Equation 2 replaced with the term $U_f \cdot \ell_f$ to represent the floor.

Equation 1 Asymmetric Thermal Coupling Coefficient

$$L^{2Da} = \frac{Q_1}{(T_i - T_e)}$$

Equation 2 Asymmetric Linear Thermal Transmittance

$$\Psi_1 = L^{2Da} - (U_{w1} \cdot \ell_{w1})$$

The thermal bridging calculations for the party wall junction indicate that the application of IWI to the external wall and party wall could reduce the surface temperature of walls in the neighbouring dwelling where thermal upgrading is only undertaken on one side of the party wall. Calculation TB/12 for the party wall before renovation work shows that the lowest temperature factor (f_{Rsi}) occurs at the corner between the party wall and the external wall, as shown in Figure 5-1. A f_{Rsi} of 0.718 was calculated for both sides of the party wall junction before renovation. This is below the critical temperature factor (f_{CRsi}) of 0.750 as identified in IP 1/06 (Ward, 2006) and is deemed to present a potential risk of mould growth in dwellings. Where renovation only occurs to one side of the party wall, the f_{Rsi} reduces in the un-renovated dwelling to 0.672 as shown in calculation TB/08 when 100mm IWI is applied to the external wall in the renovated dwelling. The f_{Rsi} reduces further in the un-renovated dwelling to 0.670 as shown in calculation TB/07 when 150 mm IWI is applied to the external wall in the renovated dwelling as shown in Figure 5-2.

Calculations TB/07 and TB/08 indicate that the application of IWI to a dwelling on one side only of a party wall could cause the deterioration of conditions on the other side of the party wall where that neighbouring dwelling is not thermally upgraded. This unintended consequence potentially increases the risk of mould growth. This finding corresponds with similar observations made by others (Little & Arregi, 2011; Weeks *et al*., 2013; National Standards Authority of Ireland, 2014) that the asymmetric reduction of heat flow into party wall junctions as a result of thermally upgraded works could be a cause for concern. It is considered that the level of risk would be highly dependent on the use of the adjacent room and occupant behaviour.

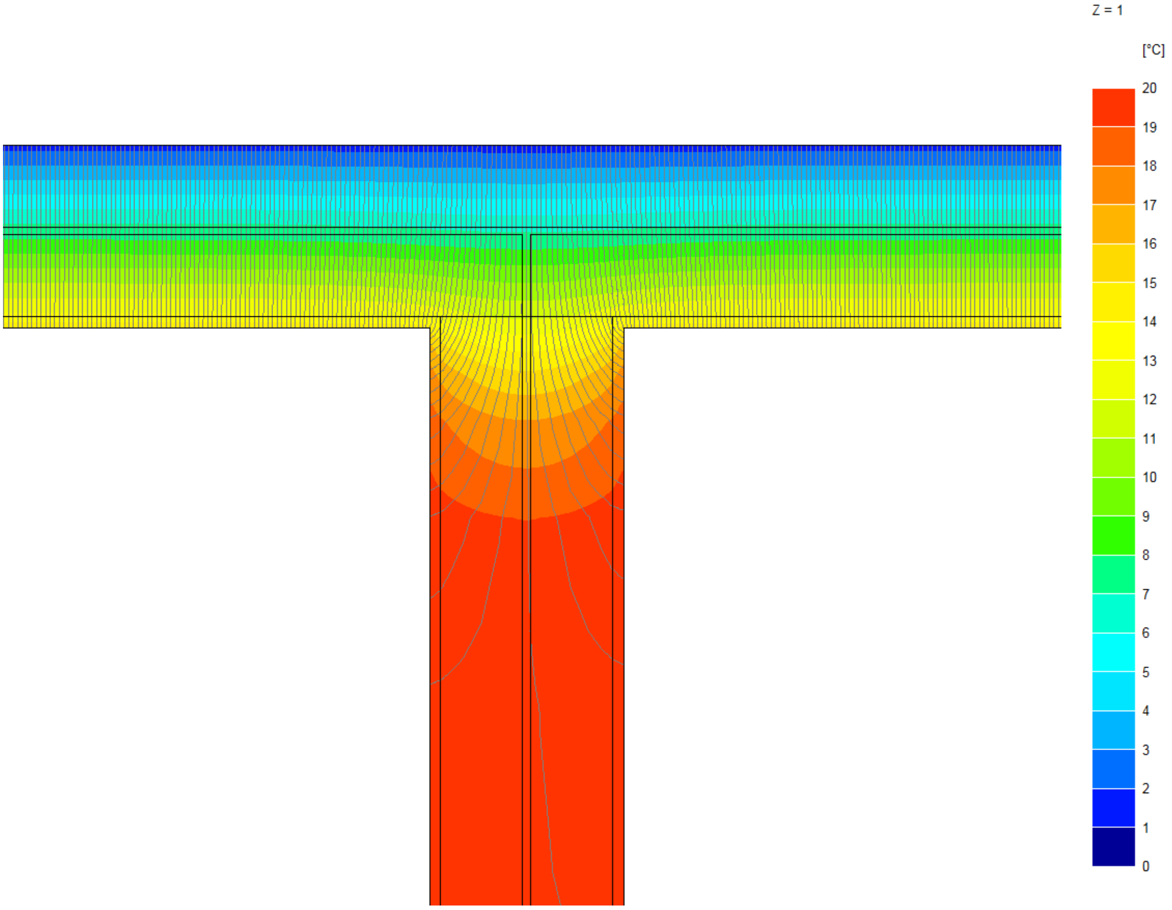

Figure 5-1 Temperature distribution for uninsulated party wall junction (TB/12)

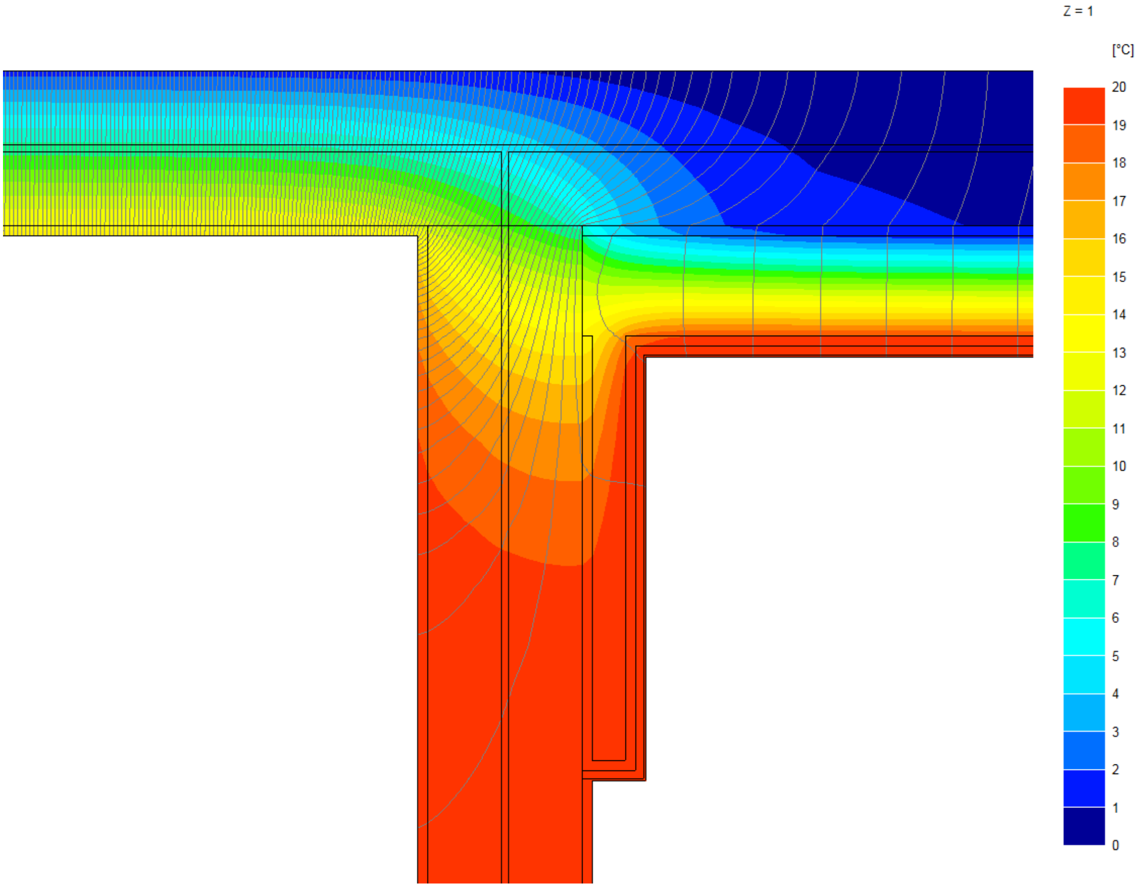

Figure 5-2 Temperature distribution of party wall single-sided IWI thermal upgrade (TB/07)

Thermal bridging calculations TB/05, TB/15 and TB/16 were undertaken to investigate the effect of returning insulation along the party wall. TB/16 had no insulation returning along the party wall and resulted in a Ψ-value of 0.169 W/m·K to be applied to each dwelling. TB/05 had an insulation return of 600 mm and resulted in a Ψ-value of 0.107 W/m·K to be applied to each dwelling. TB/15 had insulation returning the full length of the party wall resulting in a Ψ-value of 0.103 W/m·K to be applied to each dwelling. The installation of an insulated return 600 mm in length improved the Ψ-value by 37% and a full return improved the Ψ-value by 39 % when compared to the junction with no return of insulation. There is only a 3 % difference in improvement in the thermal bridging between the design solution with a 600 mm return of insulation and the detail with a full return of insulation along the party wall.

Calculations TB/09 and TB/14 were prepared to explore the effect of returning insulation along solid masonry partitions. The designer considered the main issue with partitions to be space for including the return of insulation on both sides of a partition. It was decided to examine the difference between returning insulation along both sides of a partition and returning insulation along a single side. A return length of 600 mm was specified for both calculations.

The return length was proposed by the designer, however, it is acknowledged that there will be instances where this will differ in practice. Calculation TB/09 included insulation returning both sides of the partition and resulted in a Ψ-value of 0.097 W/m·K. Calculation TB/14 had insulation retuning along a single side of the partition and resulted in a Ψ-value of 0.158 W/m·K. Returning insulation along a single side of the partition increased the Ψ-value by 63 % when compared to the junction with insulation returned along both sides.

Inspections of the solid brickwork external walls at the properties under assessment have revealed that the volume between the two masonry leaves tied together with headers is not completely filled with mortar. The cavity shown in Figure 5-3 is largely composed of air with a fraction of brick headers and mortar. Thermal modelling was undertaken to assess the effect of a notional air cavity on the Ψ-value and f_{Rsi} of each junction design. An equivalent thermal conductivity (λ_{eq}) was calculated for the air cavities. The heat flow in the cavities in the ground floor, party wall and partition junctions was deemed to be predominately horizontal permitting a single λ_{eq} to be calculated for the air cavity layer in these thermal models. Based on the bonding of the masonry shown in Figure 5-4, a brick header fraction of 0.054 and an air fraction of 0.946 were calculated using measurements obtained on site. A λ_{eq} for the air layer was calculated as 0.105 W/m·K using Equation 3 by inputting a λ of 0.067 W/m·K for the air (BSI, 2007) and a λ of 0.770 for the brick headers (Anderson, 2006). The λ_{eq} of the mortar filled cavity layer was calculated as 0.931 W/m·K using the same fractions but the λ of air was exchanged for the λ of mortar. The quantity of mortar in the air cavity could not be determined and as a result in the calculation was simplified to exclude the effect of the mortar droppings.

Figure 5-3 Cavity in Solid Brickwork External Wall

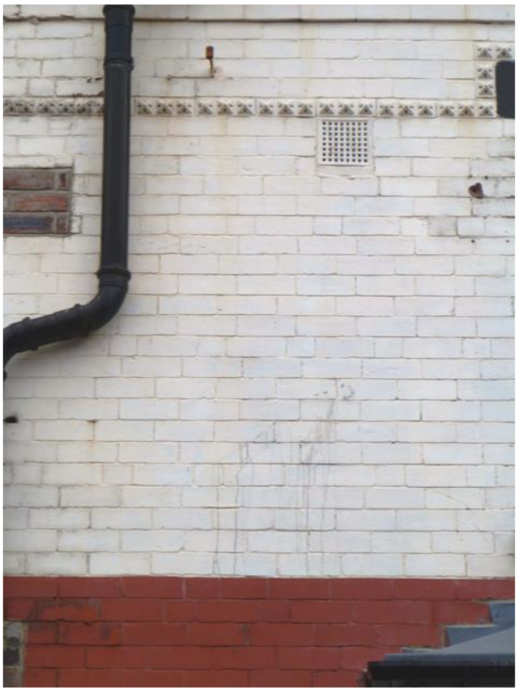

Figure 5-4 Brickwork Bonding

Equation 3 Equivalent Thermal Conductivity of Air Cavity

$$\lambda_{eq} = (F_{brick} \times \lambda_{brick}) + (F_{air} \times \lambda_{air})$$

Where:

F_{brick} = Fraction of Material
λ_{brick} = Thermal Conductivity of Material
λ_{eq} = Equivalent Thermal Conductivity

The heat flow in the cavity present in the party wall/ground floor junction was considered to be predominantly vertical in nature. Therefore, the cavities in these models were divided into sections following the conventions in BR 497 (Ward & Sanders, 2007) with a λ_{eq} calculated for each. Calculations TB/01 and TB/20 for the ground floor junction both show a Ψ-value of 0.016 W/m·K indicating no difference between the junction incorporating a mortar filled cavity and that with an air filled cavity. The calculations TB/11 and TB/19 for the party wall/ground floor, TB/05 and TB/13 for the party wall and TB/09 and TB/21 for the partition all show a 3 % improvement for the junctions including the air cavity.

5.5 Thermal bridging conclusions

The following conclusions can be drawn from the findings of this report:

Published conventions are required to proportionally assign a Ψ-value to junctions that include party walls where the treatment of the thermal envelopes are different on both sides of that party wall. If accurate design predictions of whole building energy use and CO_2 emissions for works to existing buildings are to be made, then it is necessary to assess the impact of junctions by calculation in an appropriate and standardised manner. This report has demonstrated a potential procedure for calculating asymmetric Ψ-values to party wall junctions.

Where adjoining properties are not subject to a thermal upgrading scheme with IWI applied there is an increased potential risk of mould growth occurring. This could have implications for developers because the findings in this report suggest that the installation of IWI to one property can cause a deterioration of the conditions in the adjoining property if it is not thermally upgraded in the same way. Where two adjoining properties are in different ownership there could be legal consequences.

There is a 3 % difference in thermal bridging between the design solution with a 600 mm return of insulation and the design with a full return of insulation along the party walls. It is considered that a time and cost analysis is required to determine whether the 3 % improvement in thermal bridging is outweighed by the programme and financial implications of installing IWI along the full extent of party walls. However, it is acknowledged that other factors may influence the decision to include IWI returns, for example, space limitations, aesthetics and architectural detailing requirements.

The thermal bridging calculations presented in this report demonstrate that a 63 % increase in thermal bridging can occur where IWI is only returned along a single side of a solid masonry partition. Where spatial, aesthetic and architectural detailing requirements permit, insulation should be returned along both sides of solid masonry partitions for the purposes of reducing thermal bridging.

Observations made in preparation for the calculations presented in this report indicated that solid brick wall construction can include a cavity that is mainly composed of air. Based on the limited sample of junctions thermally modelled, only a small increase in performance is obtained when the wall cavity is taken to be filled with air rather than mortar. The effect is considered small but the impact on whole dwelling energy use and CO_2 emissions calculations needs to be confirmed. In addition, the actual air exchange rate for cavities in solid wall construction could have an impact on the λ_{eq} of the air cavity layer and this warrants further investigation.

5.6 Thermal bridging recommendations

The following recommendations are made based on the conclusions of this report:

Conventions should be developed and published for proportionally assigning Ψ-values to junctions that include party walls where the treatment of the thermal envelops are not the same on both sides of the party wall.

Thermal upgrading schemes that include junctions with separating elements should have thermal bridging calculations undertaken to assess the potential risk of mould growth where the adjoining property will remain un-renovated.

A time and cost analysis should be undertaken for the options for returning IWI along the party walls. The results of the time and cost analysis should be considered in conjunction with the results of the thermal bridging calculations presented in this report.

IWI should be returned along both sides of solid masonry partitions where spatial, aesthetic and architectural detailing requirements permit.

The effect of the air cavity within solid brickwork walls on whole dwelling energy use and CO_2 emissions should be investigated.

The properties of the air cavity layer should be ascertained by measurement in field tests.

5.7 Thermal bridging references

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6 Hygrothermal behaviour

6.1 Overview of hygrothermal simulations

This section of the report presents the results of hygrothermal simulations that were undertaken as part of the building fabric performance modelling to assess the hygrothermal performance of a selection of building fabric design details. These related to the renovation and thermal upgrading of brick built terrace properties constructed circa 1900 in Leeds. The design retrofitted the existing solid brickwork external walls with IWI. An external wall with 150 mm IWI and another external wall with 100 mm IWI were modelled to investigate the hygrothermal performances of the two design options.

6.2 Problem description for hygrothermal investigation

6.2.1 Definition of investigation

A meeting was held with the project designer to inform the modelling work. One-dimensional hygrothermal simulations were undertaken in accordance with BS EN 15026 (British Standards Institute, 2007) for the external wall plane elements to assess the predicted conditions within the existing masonry and investigate the potential for frost damage. Concerns raised in the findings of the one-dimensional simulations necessitated the undertaking of additional modelling work that utilised two-dimensional hygrothermal simulations to investigate the potential implications for the existing timber floor joists to the ground and intermediate floors. The subject suspended ground floor is over a partially exposed cellar.

6.2.2 Simulation limitations

The contents of this report relate to the one and two-dimensional hygrothermal simulations undertaken to investigate the hygrothermal performance of the main external wall areas and the connecting floor junctions only. The results and findings are geographically specific for the plane elements and junctions modelled. Materials data for the bricks, mortar and air cavity to the solid masonry external walls had to be selected from a database of materials because site specific measured values were not available. The results and findings reported for the hygrothermal simulations are to be used to inform an overall assessment of moisture risk, they are not proof of risk or safety.

6.2.3 Subjects of simulations

The construction of the external wall plane elements that formed the subjects of the one-dimensional hygrothermal simulations were as follows:

Subject 1

- Finish plaster on 12.5 mm plasterboard

- 10 mm air cavity
- 150 mm Polyisocyanurate (PIR) insulation
- 10 mm air cavity
- 230 mm brickwork

Subject 2

- Finish plaster on 12.5 mm plasterboard
- 10 mm air cavity
- 100 mm PIR insulation
- 10 mm air cavity
- 230 mm brickwork

Details for the ground and intermediate floor junctions that formed the subjects of the two-dimensional hygrothermal simulations are shown in Figure 6-1, Figure 6-2 and Figure 6-3. The junctions were modelled for both 100 mm and 150 mm IWI scenarios.

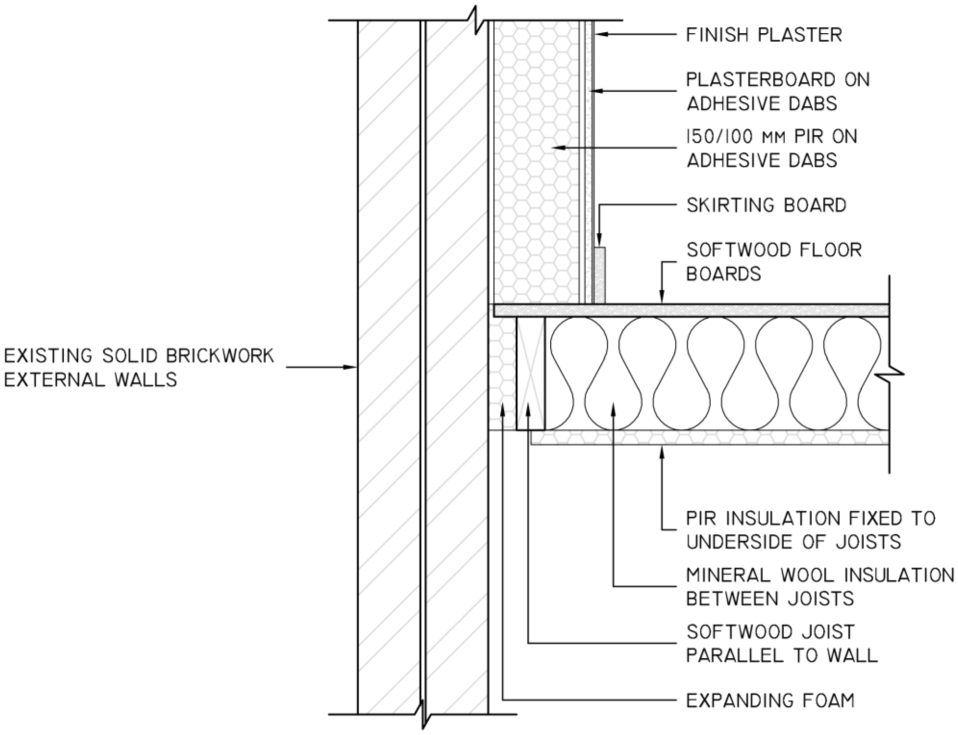

Figure 6-1 Ground Floor Junction with Joist Parallel to External Wall

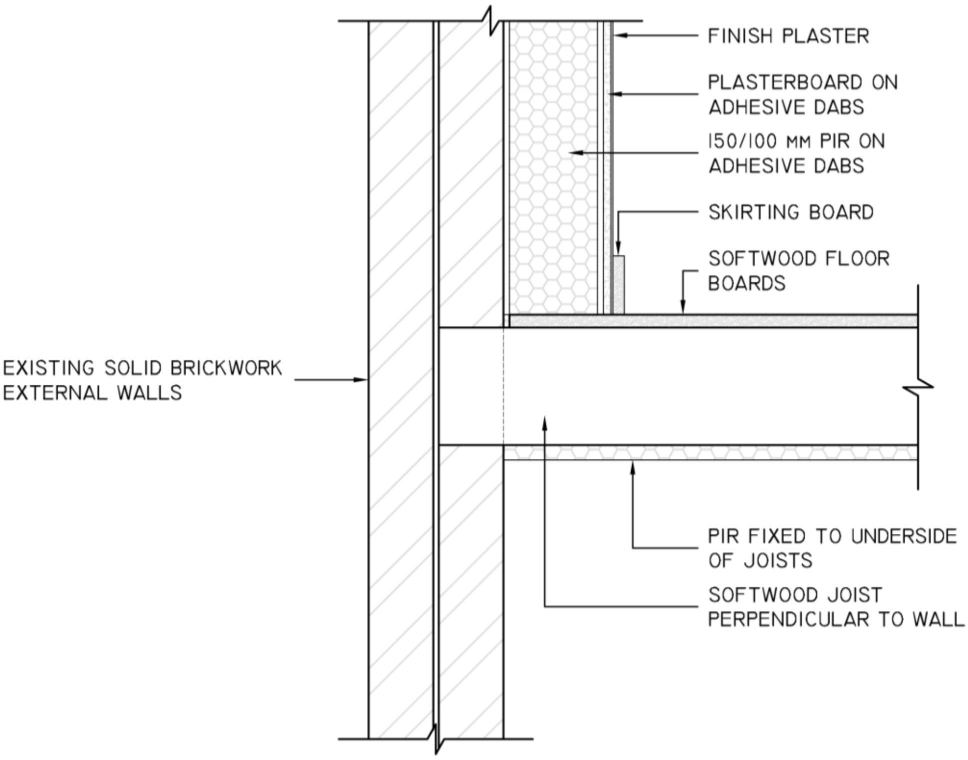

Figure 6-2 Ground Floor Junction with Joist Perpendicular to External Wall

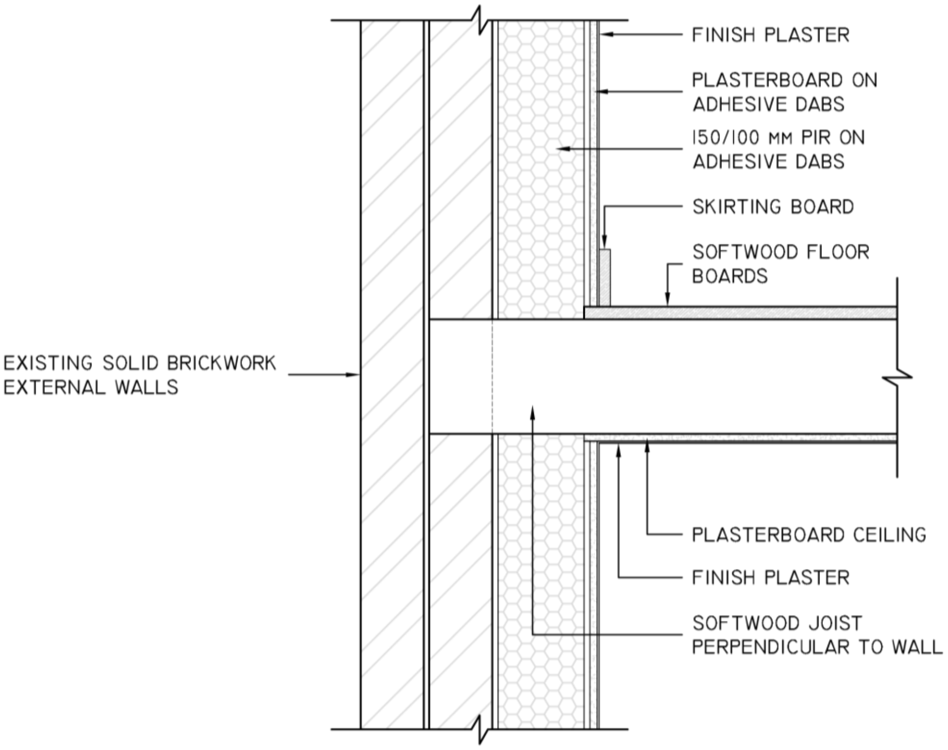

Figure 6-3 Intermediate Floor Junction with Joist Perpendicular to External Wall

6.2.4 Simulation periods

Initial one-dimensional hygrothermal simulations were based on a three year (26280 hours) period beginning on the 1st of October 2013. As a result of the findings from these initial simulations, the time period was extended to 10 years (87600 hours) for a selection of simulations to investigate the total water content over a longer term. The two-dimensional simulations were based on a one year (8760 hours) period. These were limited to one year because of the complexity of the models and the computational time required to process the two-dimensional simulations.

6.2.5 Initial conditions

The initial temperature was set at 20°C and the initial relative humidity was 80%. The initial water content for each layer of the constructions can be seen in Appendix H.

6.2.6 Boundary conditions

External Climate

A reference year composed of hourly data was created for the Leeds site location using the Meteotest Meteonorm version 7 software (Meteotest, 2012).

Internal Environment

The *EN 15026 Indoor Climate* option was selected in the WUFI Pro (Fraunhofer Institute for Building Physics, 2014a) and WUFI 2D (Fraunhofer Institute for Building Physics, 2014b) hygrothermal simulation software programs. The cellar boundary condition in the two-dimensional simulations was defined using a sine curve function with a mean temperature of 15°C with amplitude of 7°C, and a mean relative humidity of 80% with amplitude of 10%.

6.2.7 Material parameters

All materials included in the models were selected from the WUFI materials databases (Fraunhofer Institute for Building Physics, 2014a; Fraunhofer Institute for Building Physics, 2014b). Appendix H contains the data for the materials used in the hygrothermal simulations. Ascertaining the properties of the existing masonry external walls beyond measuring the geometry of the brickwork was outside the scope of the project. Therefore, the material *solid brickwork masonry* was selected from the WUFI databases (*ibid*). The unknown properties of the existing masonry external walls and the inclusion of the *solid brickwork masonry* material from the WUFI databases (*ibid*) in the simulations reduces confidence in the reliability of the results.

Inspections of the brickwork external walls at the properties under assessment revealed that the volume between the two masonry leaves tied together with headers were not completely filled with mortar. The cavity shown in Figure 5-3 (page 63) is largely composed of air. A fraction of brick headers and mortar were observed within the cavity. Figure 5-4 (page 64) shows the bonding pattern to the brickwork. The hygrothermal bridges created by the brick headers and mortar were ignored in order to simplify the hygrothermal simulations. The nature and rate of any air exchange to the cavity could not be established so 10 mm air layers from the WUFI databases (*ibid*) were input to the simulations.

6.3 Hygrothermal models and numerical solutions

6.3.1 Simulation tools

All one-dimensional hygrothermal simulations were undertaken using the Fraunhofer Institute for Building Physics WUFI Pro version 5.3 software (Fraunhofer Institute for Building Physics, 2014a). All two-dimensional hygrothermal simulations were undertaken using the Fraunhofer Institute for Building Physics WUFI 2D version 3.4 software (Fraunhofer Institute for Building Physics, 2014b).

6.3.2 Numerical simulations

Details of the numerical simulations are presented in Appendix H.

6.4 Hygrothermal simulation results and findings

The results presented throughout this section of the report relate to the constructions in a Southwest orientation because this represented the highest external moisture load caused by wind driven rain as identified from an analysis of the external climate file.

6.4.1 Total water content

Figure 6-4 shows the total water content over a three year simulation period for all cases of the external wall plane elements. It can be seen in Figure 6-4 that the base wall reaches a state of dynamic equilibrium after the effect of the initial conditions have been mitigated. It can also be seen in Figure 6-4 that the total water content increases over the three year simulation period for the wall constructions thermally upgraded with IWI.

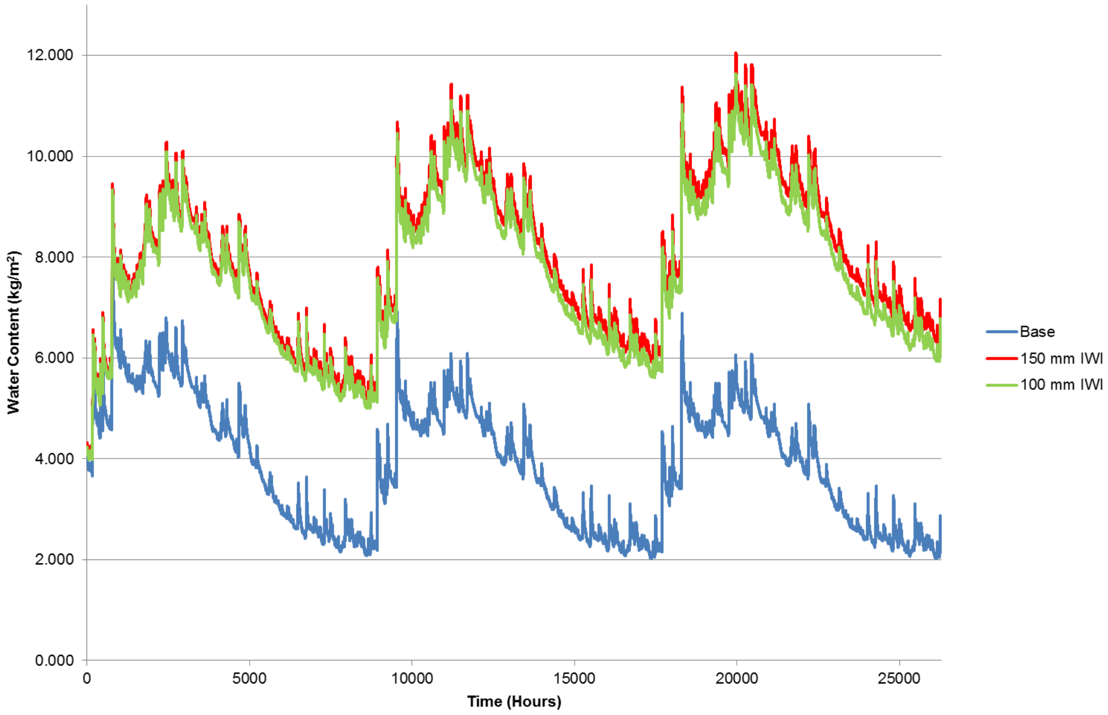

Figure 6-4 Total Water Content 3 Years

In order to investigate the extent of water accumulation identified in the thermally upgraded walls, the simulation period was extended to 10 years. Figure 6-5 shows that the total water content continues to increase over the first nine years of the extended simulation period. The long period of water accumulation provides sufficient time for potential deterioration of the building fabric to occur.

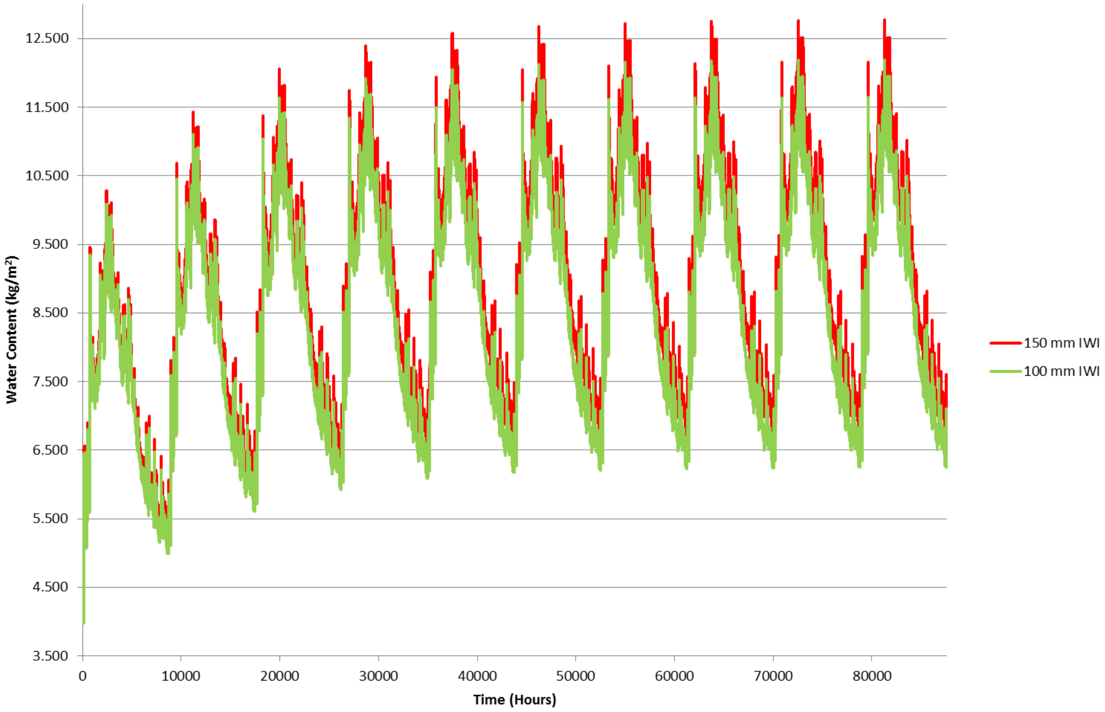

Figure 6-5 Total Water Content 10 Years

6.4.2 Conditions within masonry inner leaf

A check of the water content within each layer of the wall constructions revealed that the highest accumulation of moisture was predicted to occur within the masonry inner leaf of cases where the walls were thermally upgraded with IWI. The accumulation of moisture is considered to be caused by the installation of the IWI in two ways. Firstly, the IWI reduces heat input to the masonry that would otherwise promote outward drying. Secondly, the IWI creates a barrier against evaporation of moisture to the internal environment. Clay brickwork is hygroscopic in nature and it absorbs moisture from the surrounding air and the rain falling on the external surface. Wind driven rain substantially increases the amount of water available for absorption. Liquid transport mechanisms redistribute absorbed water through the pores of the brickwork but the installation of the IWI removes some of the drying potential leading to moisture accumulation within the masonry. Figure 6-6 shows the rate of water accumulation to the masonry inner leaf for the walls upgraded with IWI. The un-insulated base wall can be seen in Figure 6-6 to reach a state of dynamic equilibrium after the effects of the initial conditions have been mitigated.

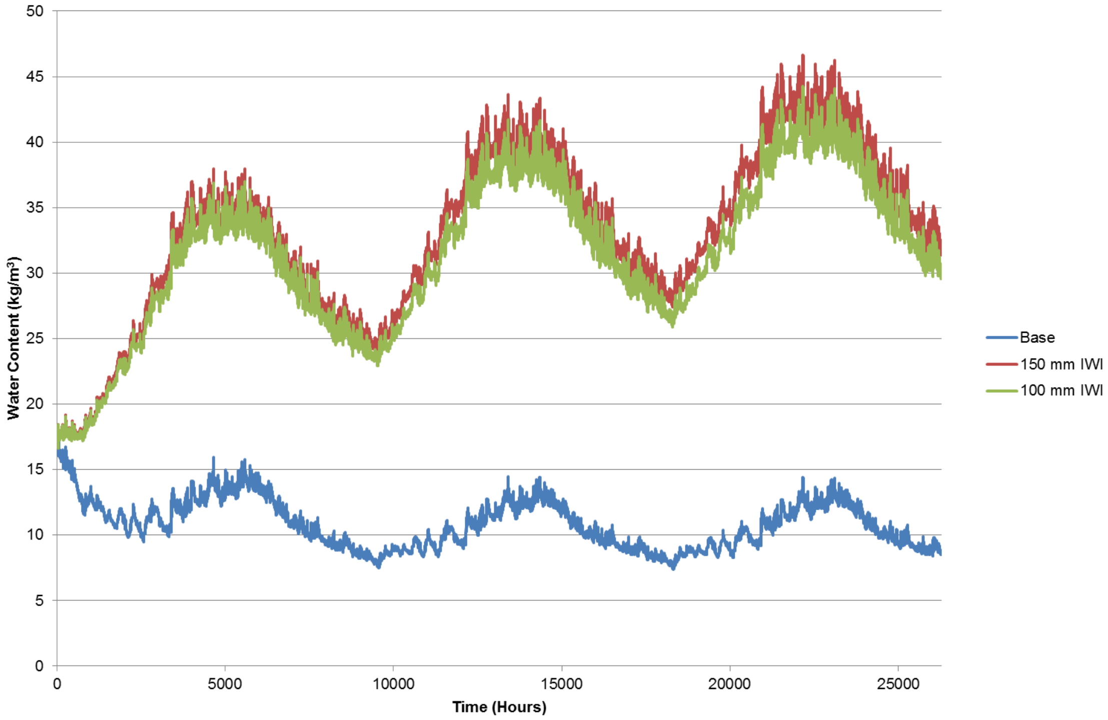

Figure 6-6 Water Content of Masonry Inner Leaf

The discovery of moisture accumulation to the masonry inner leaf necessitated that the predicted temperature and relative humidity also be examined at this location. Relative humidity above 80% permits mould growth and can promote fungal growth to embedded timbers (British Standards Institute, 2011). Dry rot favours temperatures around 23°C (Douglas & Stirling, 1997) with 20°C used to assess risk in the analysis of hygrothermal simulations. Figure 6-7, Figure 6-8 and Figure 6-9 show the temperature and relative humidity predicted in each case. During the simulation period of 26280 hours (three years) the relative humidity within the base wall exceeded 80% for 367 hours (1.4%) with a temperature above 20°C for 195 hours (0.7%) of those hours. The wall upgraded with 150 mm IWI exceeded 80% relative humidity for 25699 hours (97.8%) with a temperature above 20°C for 1830 (7.0%) of those hours.

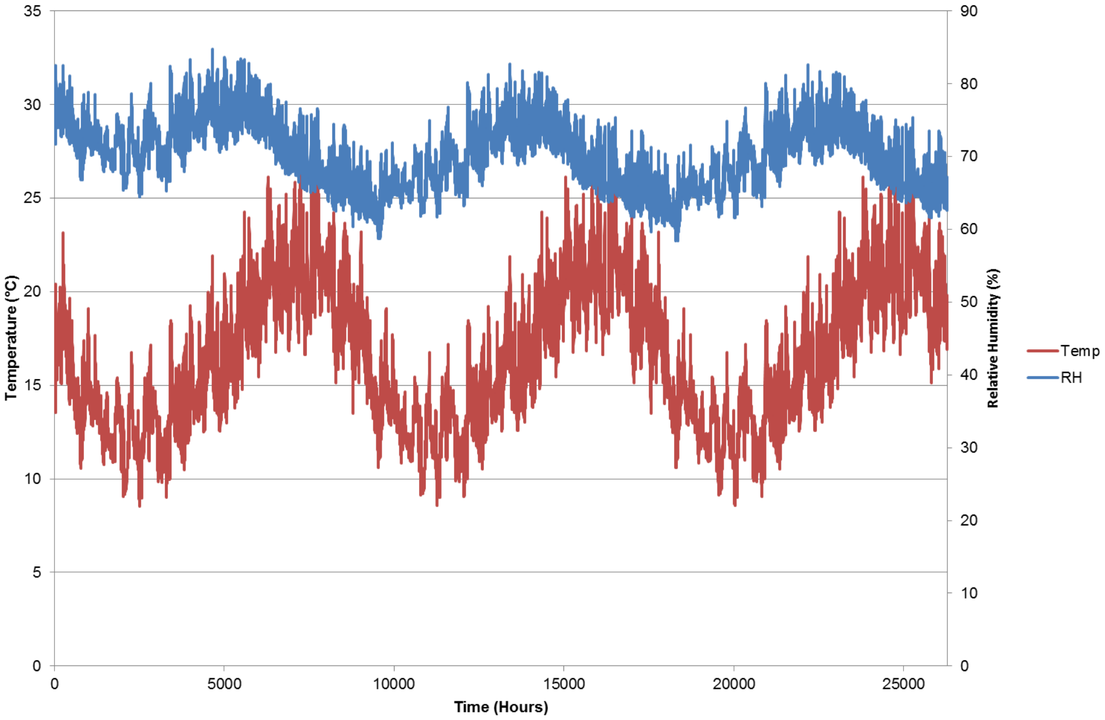

Figure 6-7 Temperature and Relative Humidity of Base Wall Inner Leaf

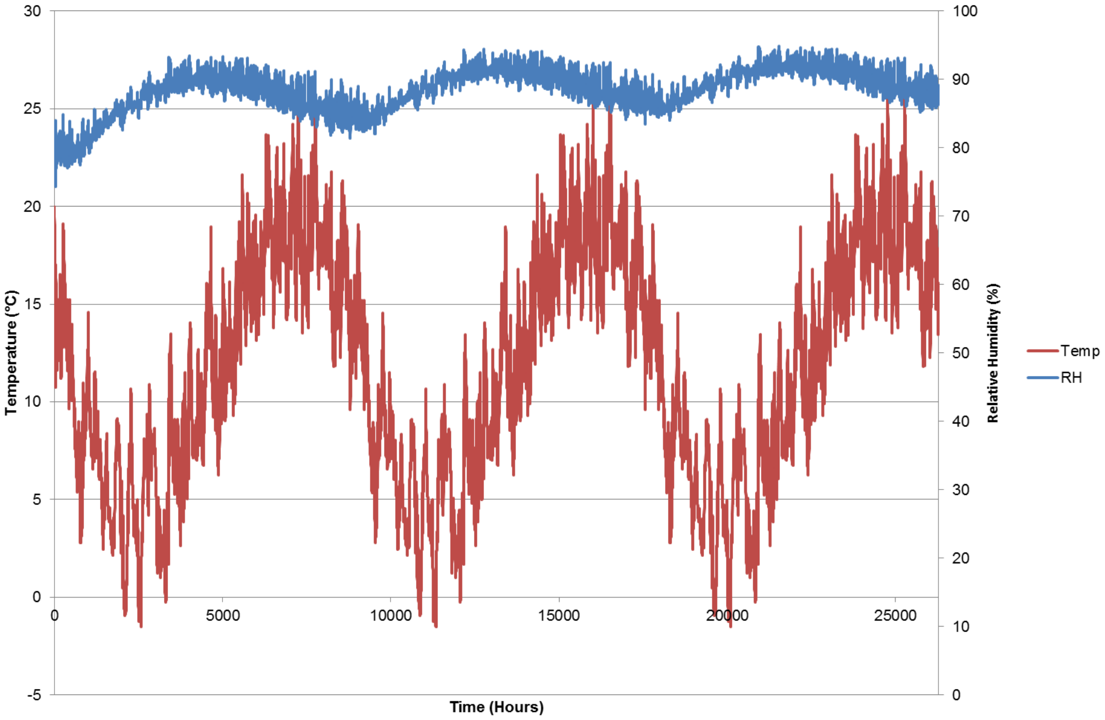

Figure 6-8 Temperature and Relative Humidity to Inner Leaf of Wall Upgraded with 150 mm IWI

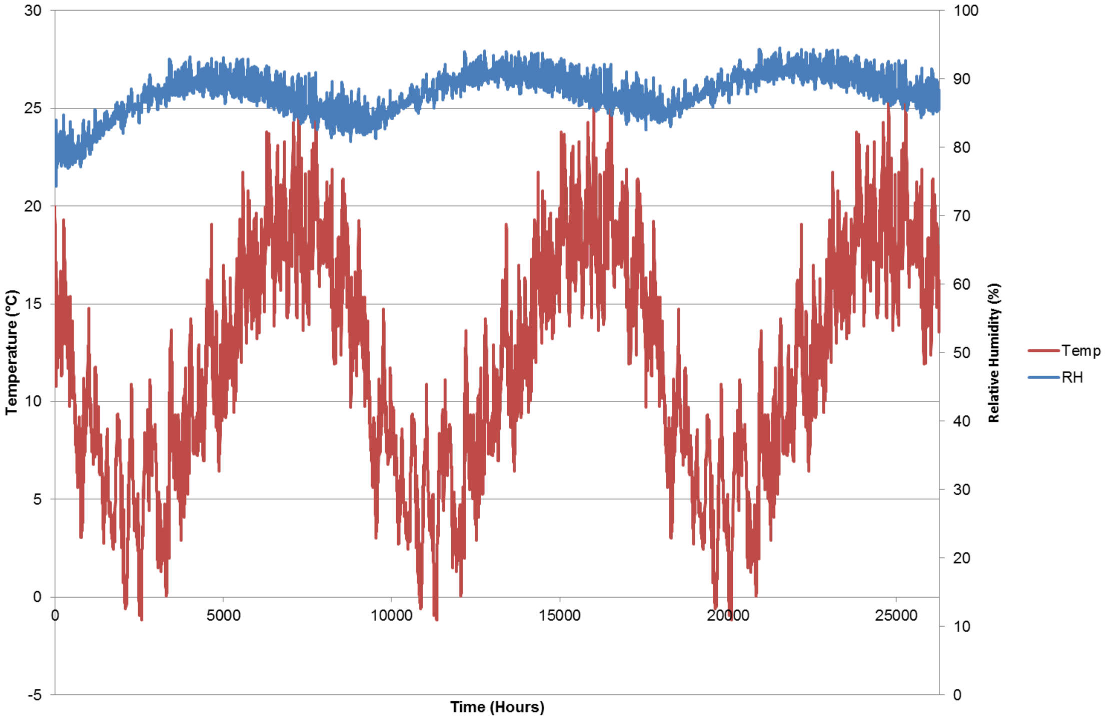

Figure 6-9 Temperature and Relative Humidity to Inner Leaf of Wall Upgraded with 100 mm IWI

The relative humidity within the wall upgraded with 100 mm IWI exceeded 80% for 25642 hours (97.6%) with a temperature above 20°C for 1902 (7.2%) of those hours. The relative humidity within the un-insulated base wall can be seen in Figure 6-7 to reach a state of dynamic equilibrium after the effects of the initial conditions have been mitigated. The relative humidity within the upgraded walls can be seen in Figure 6-8 and Figure 6-9 to be increasing over the simulation period. The predicted increase in relative humidity corresponds to the predicted increase in water content. The conditions simulated within the inner leaf of the walls upgraded with IWI raise concerns over the potential of rot to any timbers that are embedded into the walls. The one-dimensional hygrothermal simulations predict high levels of relative humidity within the upgraded walls that mark a substantial increase when compared to the base wall. The temperatures within the upgraded walls are also sufficient for fungal growth to occur.

6.4.3 Conditions within timber joists

Two-dimensional hygrothermal simulations of the ground and intermediate floor junctions were prepared to further explore the concerns raised from analysis of the one-dimensional simulations. Versions of the ground floor junctions were modelled with joists parallel and perpendicular to the masonry external wall. The intermediate floor was modelled with joists perpendicular to the external wall. These configurations were chosen to investigate the effects of the predominant moisture loads at each location. Timber to the underside of the parallel ground floor joists, and to the ends of the perpendicular ground floor and intermediate floor joists were deemed to be of greatest concern because these regions are either in direct contact with the masonry or positioned in close proximity to the cellar boundary condition. Maintaining a maximum timber moisture content below 20% (by mass) is critical to avoid the onset of rot and mould growth (TRADA, 2004).

Figure 6-10 shows the water contents to the bottom of the ground floor joists running parallel to the external walls. During the simulation period of 8760 hours (one year) the water content of the joist parallel to the 150 mm IWI ground floor junction exceeds 20% for 911 hours (10.4%). It can be seen in Figure 6-10 that the water content of the joist parallel to the 100 mm IWI ground junction remains below the 20% threshold for the entire simulation period. The water contents of the perpendicular joist ends to the ground floor junctions are shown in Figure 6-11. The perpendicular joists ends to the 150 mm IWI ground floor junction exceeded 20% water content for 2765 hours (31.6%). The water content of the perpendicular joist ends to the 100 mm IWI ground floor junction exceeded 20% for 2403 hours (27.4%). Figure 6-12 shows the water content to the ends of the intermediate floor joists. The water content exceeded 20% for 2809 hours (32.1%) to the perpendicular joist ends of the 150 mm IWI intermediate floor junction. The 20% limit was exceeded for 2654 hours (30.3%) to the perpendicular joist ends to the 100 mm IWI intermediate floor junction. The results of the two-dimensional hygrothermal simulations predict conditions within the thermally upgraded junctions that could promote timber rot. The results indicate that there is particular concern about timber that is embedded into masonry.

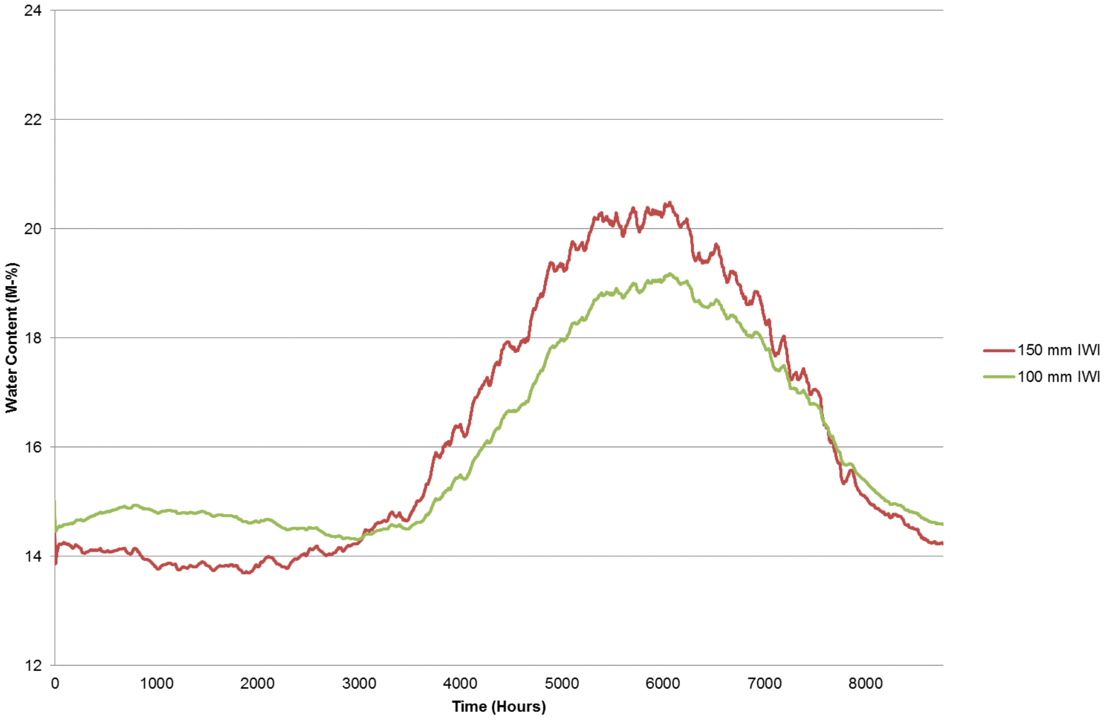

Figure 6-10 Water Content (M-%) Bottom of Parallel Ground Floor Joist

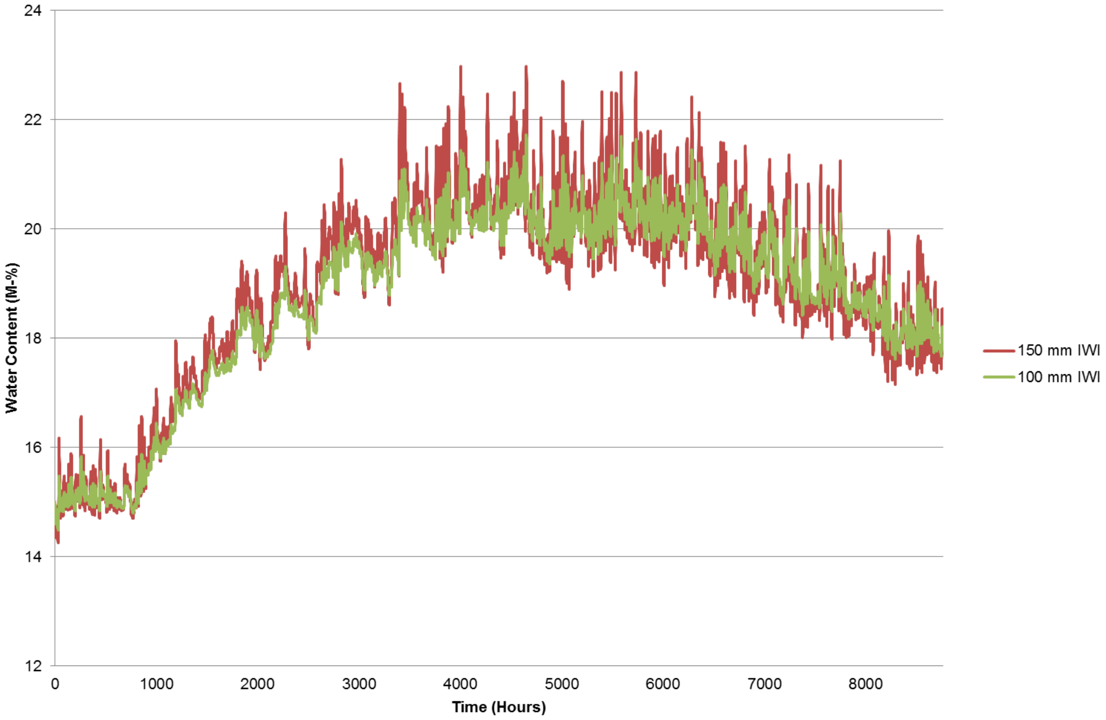

Figure 6-11 Water Content (M-%) End of Perpendicular Ground Floor Joist

Figure 6-12 Water Content (M-%) End of Perpendicular Intermediate Floor Joist

6.4.4 Frost damage

In order to assess the risk of frost damage to the brickwork outer leaf a 5.5 mm thick layer positioned between 5.5 mm and 11 mm from the outer face was examined. Assuming an approximate expansion of 10% by volume when water is converted to ice it was calculated that 216 kg/m^3 would be the critical water content for the brickwork with 24% porosity. The highest water contents simulated were 146.150 kg/m^3 (67.7%) for the un-insulated base wall, 151.640 kg/m^3 (70.2%) for the wall upgraded with 150 IWI and 151.406 kg/m^3 (70.1%) for the wall with 100 mm IWI. This means that there were zero hours at or above the critical water content during the simulation period. Furthermore, the one-dimensional hygrothermal simulations indicated that the length of time that the temperature of the brickwork layer under examination was at or below 0°C was 169 hours (0.6%) for the base wall, 822 hours (3.1%) for the 150 mm IWI and 800 hours (3.0%) for the 100 mm IWI. Based on the results of the one-dimensional hygrothermal simulations, it is considered that frost damage should not be a concern in the location simulated.

6.5 Hygrothermal conclusions

The following conclusions can be drawn from the findings of the hygrothermal simulations undertaken for this report:

a. The unknown properties of the brickwork reduces confidence in the reliability of the results presented in this report.

b. The masonry walls are not completely solid and contain an air cavity. The unknown properties of the air layer reduces confidence in the reliability of the results presented in this report.

c. The hygrothermal simulations indicate that the total water content of the walls upgraded with IWI increases overtime. The increase in total water content is predicted to continue over a 10 year simulation period and this long period of water accumulation could provide sufficient time for potential deterioration of the building fabric to occur.

d. The highest simulated water content was found in the inner leaf of the brickwork indicating that moisture could accumulate at this position. The very high levels of relative humidity predicted combined with the temperatures simulated within the masonry raise concern that there could be potential for the promotion of rot to any embedded timbers.

e. The two-dimensional hygrothermal simulations predict conditions within embedded joist ends, and the joist parallel to the ground floor junction upgraded with 150 mm IWI, that promote timber rot. Methods to mitigate this risk will need to be investigated.

f. Frost damage to the brickwork should not be a concern in the location simulated.

6.6 Hygrothermal recommendations

The following recommendations are made based on the conclusions of the hygrothermal simulation work for this report:

a. The properties of commonly encountered masonry should be ascertained by physical testing methods. A United Kingdom (UK) materials database could be compiled to assist the simulation of elements that contain materials specific to the UK.

b. The properties of air cavity layers within solid masonry walls should be investigated. The findings based upon field measurements could inform materials databases utilised for hygrothermal simulations.

c. Physical monitoring of the moisture content of embedded timbers where buildings are thermally upgraded with high levels of IWI should be conducted to further investigate the potential for timber rot.

d. The hygrothermal behaviour of thermally upgraded solid walls should be investigated for a wide range of IWI thicknesses to identify any potential critical limits.

6.7 Hygrothermal references

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7 In-use monitoring

7.1 Overview of monitoring strategy

Field trials using in-use monitoring of dwellings have been previously employed in government and academic research into domestic energy efficiency and low carbon technologies (EST, 2008, EST, 2009, DECC, 2014, Innovate UK, 2016a, Wingfield et al., 2011, DECC, 2012a, Summerfield et al., 2007).

Characterising energy use in buildings, and specifically energy use for space heating, is a complex process owing to the multiple variables associated with building fabric (infiltration, heat loss, thermal bridging, thermal mass etc.) the heating sources (boiler efficiency, heating controls, commissioning, incidental gains etc.) and the occupants (window opening behaviour, occupancy patterns, thermal comfort, domestic hot water use etc.). One method for overcoming these complexities is to incorporate them all in the data capture via in-use monitoring, and then from this net or aggregate energy base, use different analyses and disaggregate the data as required.

Incorporating all variables in the data relies on having a sufficiently large period of time both before and after an intervention to ensure that the peculiarities and variations of the dwelling and its occupants are sufficiency represented in the data from both sides of the intervention. The effect of individual differences may then be allowed for in the data set as a whole, though only if no change in the characteristic behaviour of the occupants is assumed. There is a risk of using data that is not fully representative if the data collection periods are too short or do not cover enough of the heating season.

With these constraints in mind, this two year monitoring project was established with the intention of installing monitoring equipment into 100 homes in the winter of year 1 as a “before” baseline to represent normal energy use during the heating season before any interventions had been made. Following this the insulation or new boilers would be fitted in the summer of year 1, so that winter 2 would provide the “after” data collection period. Each participant household received £20 as a token of appreciation for taking part in the research.

As described previously however, changes to the planned projects, measures, and timescales, and to funding and government policy limited recruitment opportunities. Leeds City Council were not able to resource a recruitment drive as planned and so Leeds Beckett University took on this additional role to ensure the project could continue using their contacts with local registered social landlords (RSLs). While this was successful it was not possible to retain the original experimental design and as a result dwellings yielded varying amounts of before and after data as outlined in section 7.5.1. This influences the robustness of the conclusions to some extent.

7.2 Monitoring equipment

The in-use data captured in each dwelling was, where possible; gas (m^3), electricity (kWh), internal temperature (°C) for both upstairs and downstairs, and external temperature (°C) all at half hourly time stamps.

The physical devices installed in the dwellings collecting this information are shown in Figure 7-1. It was not always possible to install all the devices in all the dwellings since some had gas meters without pulse outputs or in other cases there was insufficient space to install the equipment. The equipment was provided and installed by Yorkshire based company Orsis[3] who transmitted the data and provided visualisations via the online platform EnergyDeck. A typical screen shot can be seen in Figure 7-2.

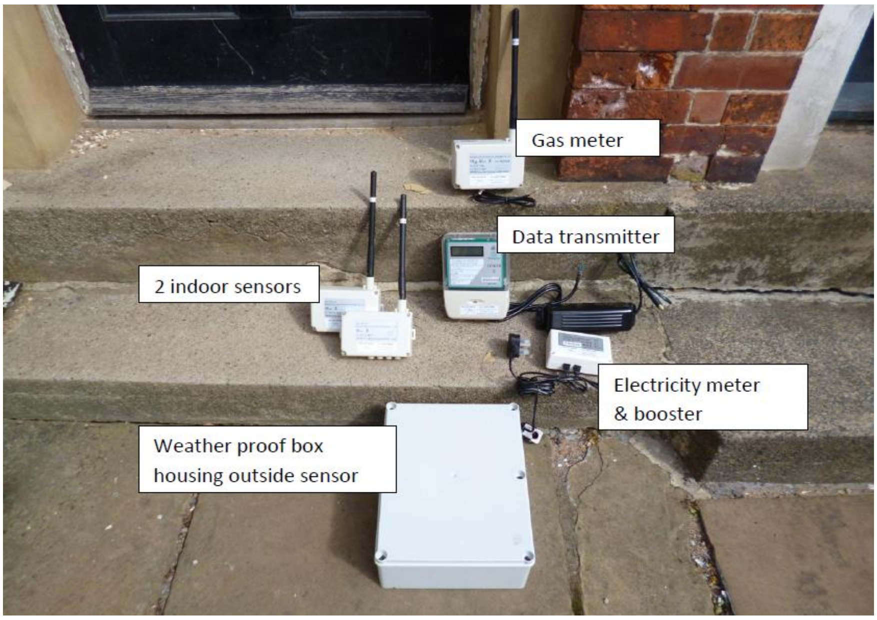

Figure 7-1 In-use monitoring equipment

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[3] www.orsis.co.uk

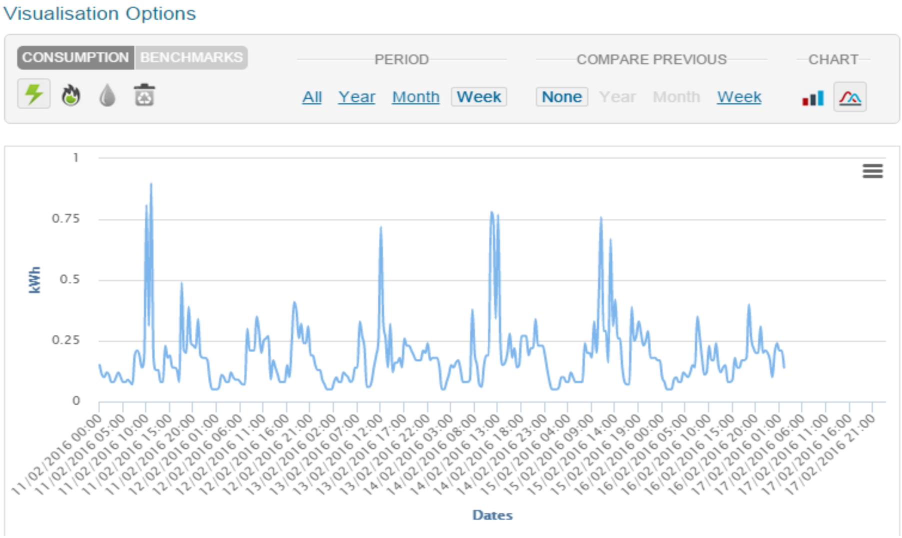

Figure 7-2 Example screenshot of visualisation platform

It was the initial intention to install this equipment in half of the houses, and in the other half to use an alternative home energy monitoring sensor provider (Tensor) and thus to compare the two systems. Unfortunately, the Tensor equipment was not ready in time to service the whole project. However, three sample Tensor systems were installed as prototypes and these are included in the sample; these are E-27, E-28 and E-42.

7.3 Representativeness and comparison with benchmark data

Almost all the dwellings in this research were provided by RSLs, thus it is important to establish if these are typical consumers. The Energy Follow Up Survey (EFUS) (BRE, 2013) identified the annual consumption rates for 1,197 gas consuming households and the electricity consumption of 1,345 households and split these according to tenure as shown in Figure 7-3 and Figure 7-4.

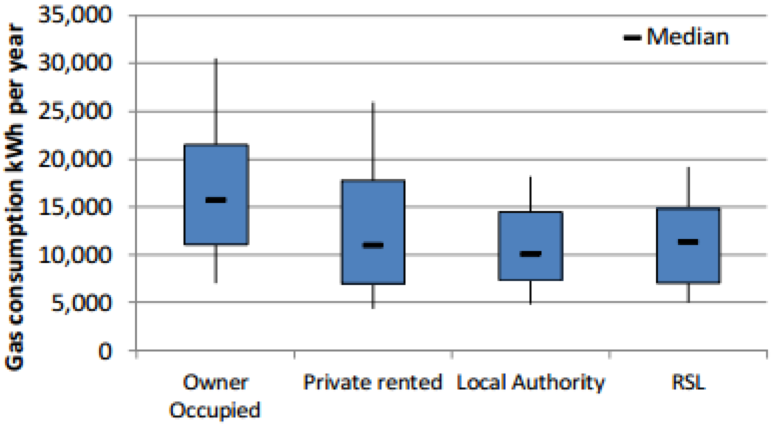

Figure 7-3 EFUS dwelling gas consumption by tenure (sourced from BRE, 2013)

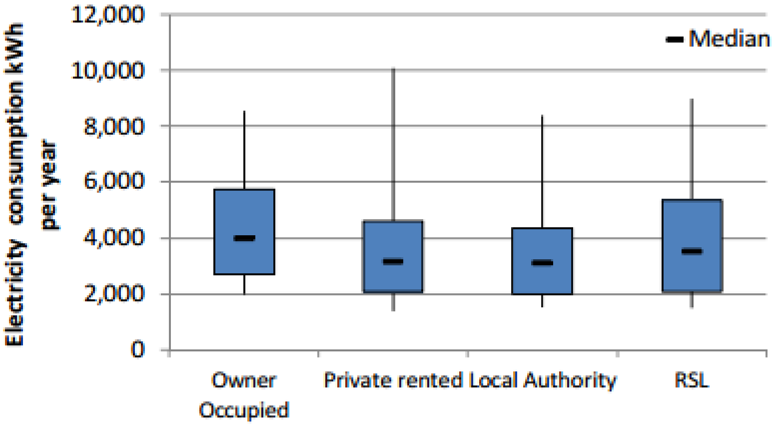

Figure 7-4 EFUS dwelling electricity consumption by tenure (sourced from BRE, 2013)

This project has only three owner occupiers and the rest are RSL tenants which are shown here to be among the lowest users of gas though considerable variation is shown with respect to electricity consumption, perhaps because of a higher proportion of electrically heated homes in RSL stock. The gas and electricity usage of the dwellings in this project, for which there was at least one calendar year of data, are relatively consistent with these national benchmarks and generally occupy the lower end of the range although there is a range in consumption, especially in the gas consumption as shown in Figure 7-5. The three outliers in electricity consumption identified in Figure 7-6 were all electrically heated dwellings with storage heaters.

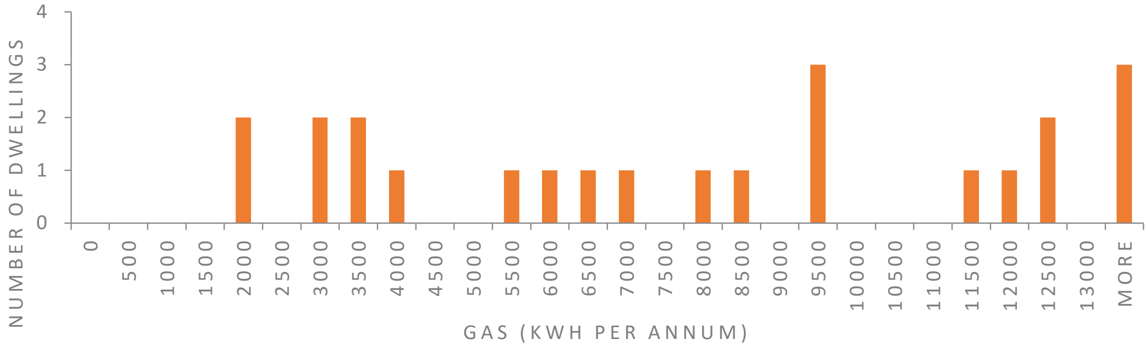

Figure 7-5 Annual gas use for sample

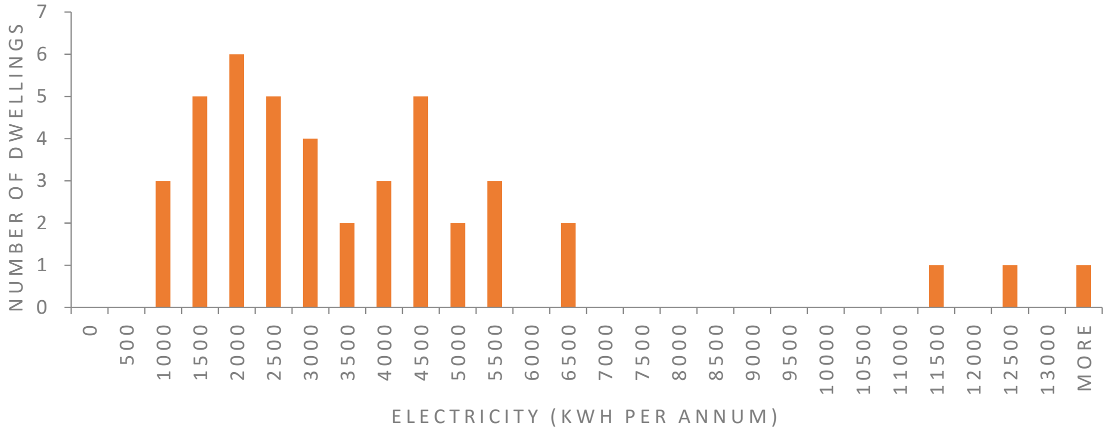

Figure 7-6 Annual electricity use for sample

It is important when contextualising the results in this project to consider house size. As shown in Figure 7-7 smaller houses use less energy but they are more energy intense, as may be expected. The house sizes in this project were mixed though most were generally below 100m^2 as can be seen in Figure 7-8. Similarly the number of bedrooms in a dwelling and the level of deprivation of the occupants is likely to affect the dwelling energy consumption (see Figure 7-9). Data were not collected with respect to the level of deprivation of the occupants; however the majority of occupants in RSL housing are unlikely to be in the least deprived quartiles. The the dwelling bedroom numbers are given in Figure 7-10.

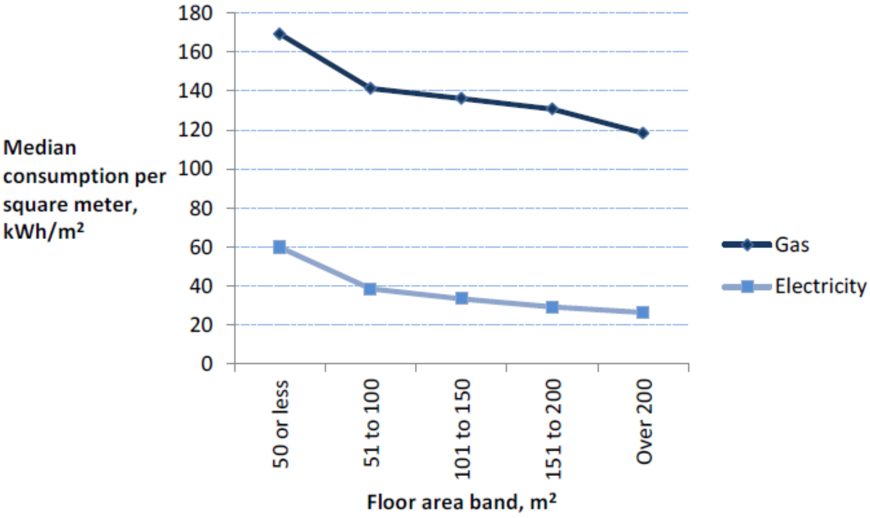

Figure 7-7 Fuel use by floor area (sourced from DECC, 2013)

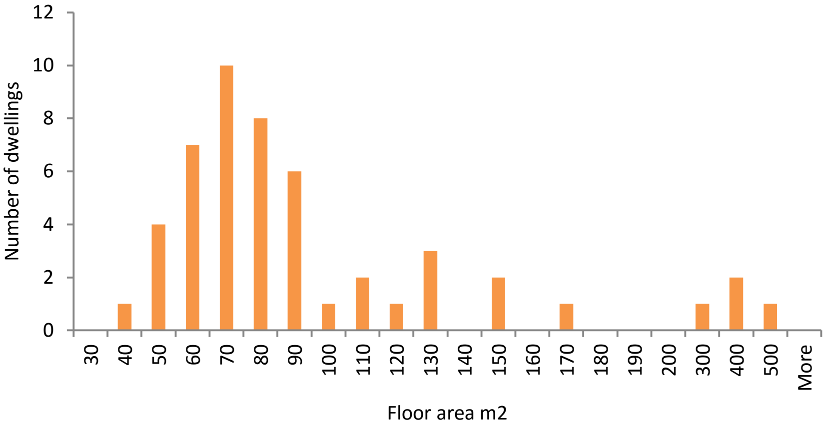

Figure 7-8 Sample dwellings' floor areas

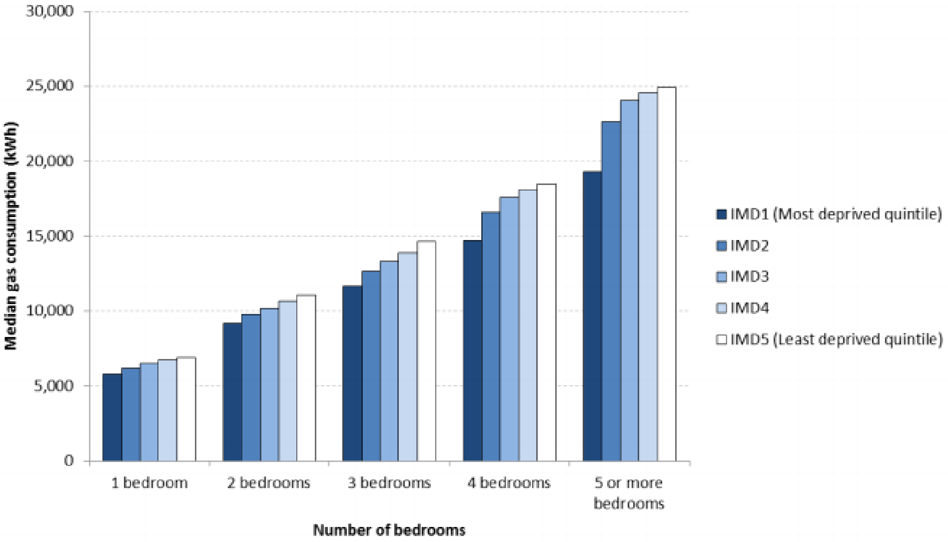

Figure 7-9 Gas consumption by bedrooms and level of deprivation (sourced from DECC, 2013)

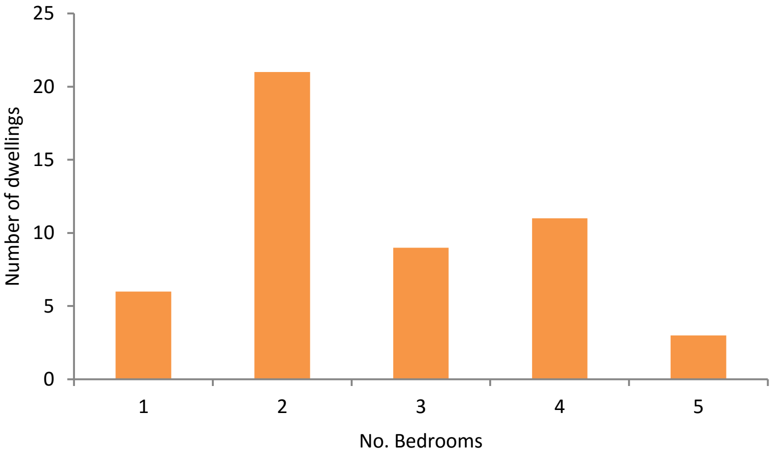

Figure 7-10 Sample dwellings' bedroom count

These benchmarks contextualise the findings in this report showing that the dwellings within the sample fall within normal consumption bands and that the majority of dwellings are relatively small.

7.4 Data analysis methodology

This project uses four different ways in which to characterise the energy efficiency of the houses and by extension therefore the effectiveness of the intervention. These are the 1) Power Temperature Gradient (PTG), 2) standard Heating Degree Day (HDD) calculations, 3) Dwelling Heat Demand (DHD) and 4) the Heating Demand Gradient (HDG). Each method is outlined below:

7.4.1 Power Temperature Gradient (PTG) rationale and method

Perhaps the simplest analysis method used is the PTG which has been previously used to describe the energy characteristics of dwellings, and make comparisons between them simply but effectively (Summerfield et al., 2015a, Summerfield et al., 2015b). To produce the PTG a scatter plot of total energy consumption and external temperature is made, where the gradient of the resulting line of best fit is the PTG. The coefficient of determination or r^2 is a statistical measure of how closely the data points fit to the line of best fit presented. An r^2 below 0.4 is taken for the purposes of this research as unreliable. This is an arbitrary selection used to remove those data sets that were particularly irregular. Those PTG with the highest correlation efficient (r^2) are the most reliable although there are no specific thresholds above which PTG are considered ‘good’.

All energy use is captured including domestic hot water, external lighting, equipment loads and space heating. The PTG provides a simple assessment procedure; although consideration should be given to the point that the fact that PTG may not accurately reflect of the energy efficiency of a dwelling in terms of space heating, since other energy uses that are not weather dependent may skew the data. However, since these energy uses are likely to be relatively consistent before and after the retrofit, the change in PGT is likely to reflect, reasonably well, the improvement in the dwelling energy efficiency.

7.4.2 Heating Degree Day (HDD) rationale and method

HDD calculations are widely used to evaluate heating demand in buildings (Carbon Trust, 2007, Fels, 1986). HDD are based on meteorological data and describe the average amount of heating required for a dwelling in a particular location given a set of assumptions about the internal conditions. These HDD are calculated for each house according to TM41 (CIBSE, 2006) based on the external temperature data collected and the use of a static 15.5°C baseline assumption (which assumes 2.5°C of internal gains and a set point temperature of 18°C) using Equation 4;

Equation 4 Half hourly heating degree day calculation

$$D_d = \frac{\sum_{j=1}^{48}(\theta_b - \theta_{o,j})\left((\theta_b - \theta_{o,j}) > 0\right)}{48}$$

Where: D_d is daily degree days, θ_b is the base temperature, and $\theta_{o,j}$ is the external temperature in the half hour j.

Calculating the HDD on a half hourly basis in this way increases accuracy over using the daily average data since it captures cold mornings and evenings in the shoulder months that may be averaged out by warm days when using daily data. Comparing the resulting HDD from this calculation to the space heating energy use over the same period provides an indication of the building's energy efficiency. Any change in the before and after energy use per HDD could therefore be an indication of the impact of the retrofit.

7.4.3 Dwelling Heating Demand (DHD) rationale and method

The static 15.5°C base temperature assumption used in conventional HDD assessments provides a basis for comparing different dwellings in the 'same' external environment. This is a simple analysis often used for aggregations of dwellings. However, HDD assumes identical internal environments and so on an individual dwelling level it may result in classification of dwellings in which occupants happen to prefer a warmer set point as inefficient and conversely, those which operate at a low set-point as more efficient.

Therefore, in order to remove the complication of different occupants having different heating behaviours an alternative assessment of the dwelling heating demand (DHD) is used. The DHD method proposed uses the same calculation as HDD however it uses the actual internal temperatures in the dwelling as a basis for the base temperature (again assuming a standard 2.5°C for internal gains). In this way an alternative DHD number can be generated as opposed to the standard HDD and this can then be compared to the space heating energy used to determine a more dwelling specific measure of the before and after energy efficiency of the dwellings.

7.4.4 Heating Demand Gradient (HDG) rationale and method

DHD plotted against energy consumption and the slope of the line of best fit in the plot is defined as the HDG. This will provide a similar analysis to the PTG; however, instead of plotting total energy against external temperature it will only plot space heating energy against DHD to assess the change in the energy efficiency of the dwelling.

7.5 Quality of the data

7.5.1 Before and after sample data collection

The project originally planned to have two winters of monitoring data; the first was proposed as the ‘before’ period and the second was intended to provide the ‘after’ data. However, as previously stated, very few of the intended retrofits actually took place. Therefore, it was not possible to secure properties where data could be collected for two full heating seasons

In addition, the way the retrofit installations were organised according to a ‘just in time’ strategy. This often meant that dwellings proposed for inclusion in the program were identified and installed with monitoring equipment sometimes only weeks before the retrofit took place. While this was not an ideal scenario the dwellings were often included as a last resort.

Figure 7-11 shows the DHD for each dwelling before and after retrofit. The longer the lines, the more data are available and therefore the more robust the conclusions are likely to be. Those dwellings with missing lines indicate where no data were collected, either because logging equipment failed, equipment could not be installed in time, or the retrofit did not take place.

It should also be noted that the retrofit start and completion times were estimated by RSLs the and there were often surprisingly few official records for each retrofit, perhaps reflecting that there is a disconnect between property owners and installers in the policy funding mechanism.

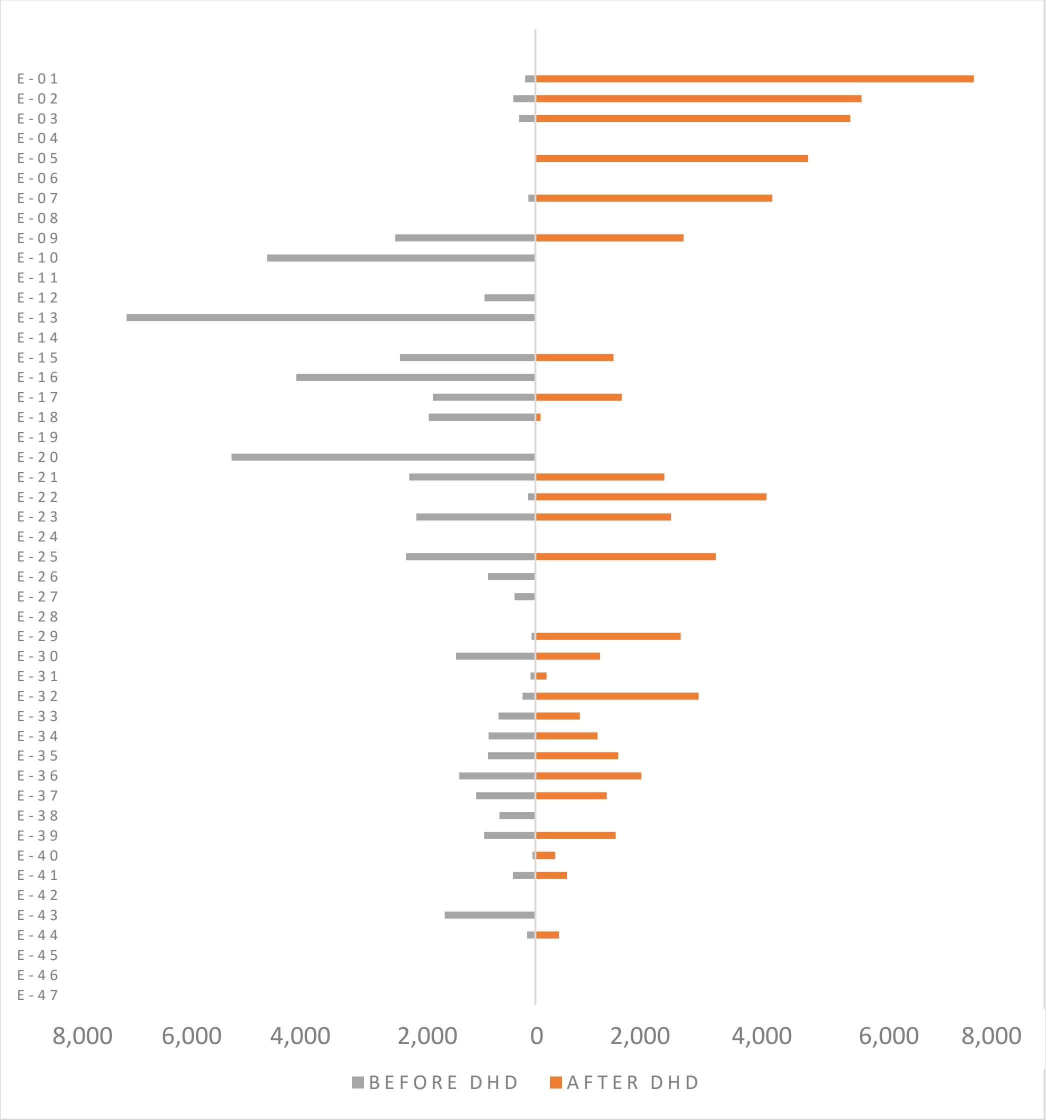

Figure 7-11 Data collection before and after retrofit

Informal discussions with peers in other institutions undertaking similar monitoring projects have identified challenges similar to those experienced in this study. It is likely therefore that any similar in-situ monitoring projects or field trials may face difficulties if technological, financial and organisational structures are similar to those experienced here.

7.5.2 Future analysis to overcome data continuity issues

In order to mitigate the data inadequacies identified in this project it might be possible to undertake further research to provide greater reliability by exploring the following techniques:

a) identify the implications of the limited data collection by investigating if there is a minimum DHD data requirement to characterise a retrofit improvement, and

b) identify possibly ways to infill the missing data by building neural network models

7.5.3 General data continuity

The data collected for each dwelling are in most instances uninterrupted though there are individual instances of data drop outs for hours, days or even weeks at a time. To deal with this complication the energy efficiency of the dwellings is only based on those periods for which there is a full set of data, i.e. data for internal temperatures, external temperature and space heating (gas or electricity). Wherever one of these inputs was not available the whole dataset for that period is rejected from the calculation process. Therefore Figure 7-11 may show dwellings with no DHD data whereas in fact some data may exist.

Only in instances where external temperature readings are missing for the entire or large proportions of the data collection period were proxy data from neighbouring dwellings used, otherwise small data dropouts are excluded from assessments. No proxy data for space heating or internal temperatures were used under any circumstances.

The data integrity for each dwelling is given in the individual project retrofit performance summary sheets available in Appendix I, giving a useful overview of the type and quality of the data collected at each dwelling.

7.5.4 Additional data considerations

There are some important variables that influence domestic heating patterns and fuel consumption for which data could not be collected in this project. The most salient are:

a) Secondary heating provision (electric or solid fuel heating),
b) Window opening behaviour (varying the number of air changes),
c) Energy use outside of the thermal envelope (outbuildings and external lighting),
d) Occupancy levels (providing additional incidental gains), and
e) Solar (shading or otherwise altering internal gains from solar irradiance).

These omissions may affect the perceived energy efficiency and comfort of the dwellings, however, it is not possible to quantify this within the constraints of this study. Where possible the interviews will be used to provide some contextual information on these influences in specific dwellings.

The following section provides a description of thermal comfort within the dwellings and how this affected the success of the retrofits before presenting the findings on the energy efficiency results of the retrofit itself.

7.6 Thermal comfort results

Thermal comfort provides a measure of how satisfied occupants are with the thermal environment in their buildings. The primary function of a building and the energy it uses, is to provide a comfortable and useful environment for its occupants. However, occupants make decisions based on personal thermal preferences; for example, heating set points and heating hours and as such thermal comfort is a complex issue.

Thermal comfort considerations influence the assessment of a retrofit measure in several ways, firstly as a metric by which success can be determined, i.e. '*did the retrofit provide acceptable thermal comfort?*', and secondly the degree to which comfort taking influences the perceived energy payback. If the dwelling was particularly inefficient initially so that occupants could not achieve comfortable conditions without excessive and often unaffordable energy use, the dwelling may have been under heated. However, following a successful retrofit the dwelling may now more easily be heated and so occupants may choose to use more energy (comfort taking) rather than achieving monetary savings.

The following section presents the before and after levels of thermal comfort in the 47 homes monitored and then discusses the extent of comfort taking that may or may not have taken place.

7.6.1 Measuring thermal comfort

There are two common approaches to establishing the thermal comfort of an environment: the *heat balance model* (Fanger, 1970; ISO 7730, 2006) which treats individuals as passive recipients of their environmental conditions; and the *adaptive comfort method* (ISO 15251, 2008; ASHRAE, 2013) which permits behavioural, physiological and psychological adaptation to the thermal environment.

The heat balance model is more suited to buildings with air conditioning systems such as offices, whereas the adaptive method is preferred for 'free running' dwellings with natural ventilation and as such the adaptive method is used in this research.

The adaptive method uses a range of internal temperatures based on the weighted mean of the external temperature within which the occupant may be assumed to be comfortable. The output of the calculation is a graph which plots the perceived comfort in the house at different external conditions. Graphs for each of the 47 dwellings in this research are presented in Appendix I in the retrofit performance summary sheets. A selection is also presented in the following sections in order to describe the patterns being observed. The plots show categories of comfort with differing expectation of comfort conditions for different occupant groups. These are:

Category 1	High expectations (primarily for sensitive or fragile occupants);
Category 2	Normal expectations (new builds and renovations);
Category 3	Moderate expectations (existing buildings); and
Category 4	Uncomfortable but permissible for short periods in certain contexts.

Internal temperatures which lie within the bands for the category 3 range (displayed on the graphs as the bold outermost lines) can be considered to be comfortable in the majority of our retrofit dwelling. However, it should be noted that since the sample was provided predominantly from social landlords there may be a higher than average proportion of vulnerable occupants where the inner most comfort bands forming category 1 might be more appropriate.

7.6.2 Adaptive thermal comfort results

The plots are shown for each house in Appendix I. These were visually assessed and from this a decision regarding the dwelling comfort could be made under the four broad comfort categories described in 7.6.1, with the first being the most comfortable and the fourth deemed uncomfortable.

In addition, Table 7-1 shows where the dwelling is generally over or under-heated and whether the temperatures are well controlled within a narrow band or uncontrolled and very variable. Several different trends were identified during the comfort analysis of the 47 homes in the extensive monitoring study and these are summarised in Table 7-1. Following this a few case studies are selected to provide more insight into the thermal comfort analysis.

Table 7-1 Thermal comfort of dwellings

Dwelling	Comfort level before retrofit	Comfort level after retrofit	Warmer after retrofit?	Noticeably under or over heated	Noticeably uncontrolled	Primary retrofit measure
E-1	3	3	No	-	-	EWI
E-2	3	3	No	-	Uncontrolled	EWI
E-3	Uncomfortable	3	Yes	Under heated	-	EWI
E-4	-	Uncomfortable	-	Under heated	-	IWI
E-5	-	3	-	-	Uncontrolled	IWI
E-6	-	3	-	-	-	IWI
E-7	-	2 & 3	-	-	-	EWI
E-8	3	3	No	-	Uncontrolled	EWI
E-9	3	3	No	Under heated	-	EWI
E-10	3	-	-	-	-	No retrofit
E-11	Uncomfortable	-	-	-	-	No retrofit
E-12	3	-	-	-	-	EWI
E-13	3	-	-	-	-	EWI
E-14	3	-	-	Under heated	-	EWI
E-15	3	3	No	-	Uncontrolled	EWI
E-16	2	2	No	-	-	EWI
E-17	3	3	Yes	Under heated	-	IWI
E-18	Uncomfortable	Uncomfortable	No	Under heated	-	EWI
E-19	3	-	-	-	-	EWI
E-20	3	-	-	-	Uncontrolled	EWI
E-21	3	3	No	-	-	EWI
E-22	3	3	Yes	-	-	EWI
E-23	3	3	No	-	-	EWI
E-24	Uncomfortable	3	Yes	Under heated	Uncontrolled	IWI
E-25	3	3	No	Under heated (overheated in winter)	-	EWI
E-26	3	-	-	-	-	No retrofit
E-27	2 (winter) & 3	-	-	-	-	IWI
E-28	1 (winter) & 3	3	No	-	-	IWI
E-29	3	3	No	Under heated	-	EWI
E-30	3	3	No	Some overheating	-	EWI
E-31	Uncomfortable	Uncomfortable	Yes	Under heated	-	EWI
E-32	3	3	No	Under heated	Uncontrolled	EWI
E-33	3	3	No	-	-	EWI
E-34	Uncomfortable	3	Yes	Under heated	-	EWI
E-35	Uncomfortable	3	Yes	Under heated	-	EWI
E-36	3	1	Yes	Under heated	-	EWI
E-37	Uncomfortable	3	Yes	Under heated		EWI
E-38	Uncomfortable	Uncomfortable	No	Under heated	Uncontrolled	EWI
E-39	3	3	Yes	Under heated	-	EWI
E-40	Uncomfortable	-	-	Under heated	-	EWI
E-41	Uncomfortable	-	-	Under heated	-	EWI
E-42	3	3	No	-	-	EWI
E-43	Uncomfortable	-	-	Under heated	Uncontrolled	IWI
E-44	Uncomfortable	Uncomfortable	No	Under heated	-	EWI
E-45	-	-	-	-	-	EWI
E-46	-	3	-	Under heated	Uncontrolled	EWI
E-47	Uncomfortable	-	-	Under heated	-	No retrofit

As can be seen in Table 7-1, in the majority of cases, the internal temperature was predominantly within the comfort range category 3 both before and after any retrofit measures. This is an important finding and confirms the observation by Bell and Lowe (2000), suggesting that most occupants are actively choosing to have a comfortable environment pre retrofit and if they are currently in inefficient homes are accepting the financial cost of this, as opposed accepting an uncomfortable environment in order to save fuel costs.

Fourteen dwellings in total were considered uncomfortably cold, and the reasons for this were explored in the interviews. In one dwelling the occupant had made the deliberate decision not to have any heating. He had recently purchased the house and had intended to install central heating but on finding out he was ineligible for funding, had decided to continue without heating. Both him and his lodger managed the cold by wearing lots of clothing layers. Other dwellings were heated but were very difficult to keep warm, usually due to draughts from doors and windows, and some also had problems with damp. Another dwelling was very large and the owners were struggling to pay the heating bills so felt forced to live in a home colder than they would like. Of these fourteen, five dwellings were brought within the comfort band 3 following the retrofit and only a further five of these remained uncomfortable following a retrofit. For the remaining four no retrofit took place.

In total there were ten dwellings that experienced a noticeable increase in average internal temperatures. In order to assess if this is related to comfort taking, it would be necessary to investigate the before and after heating energy use of these dwellings.

It is also important to consider that in a further ten dwellings the relationship between internal and external temperatures was relatively erratic which hints at an uncontrolled internal environment even after the retrofit took place. Only five of these uncontrolled dwellings were considered to be under heated.

The following are snapshots of several of the dwellings to illustrate the analysis that has taken place. Figure 7-12 shows a dwelling whose internal temperatures were consistently below the lower comfort threshold, illustrated by the bold blue line, most noticeably during colder periods. Unfortunately, the retrofit did not take place on this dwelling due to national policy and local budgeting changes and so it is not possible to assess any potential improvement. However, there is a strong indication here that the dwelling is not able to provide an adequate thermal environment, or the occupant may be actively making the choice to have a colder home or both. Data from the interviews provide insight into the experience of living in this home. The occupant is a frail elderly lady, falling within Category 1 requirements.

> *"In the winter it's absolutely bitter but in the summer it's the other way, it's over-warming, the heat. So you know I just shut the blinds and keep the sun out. So it can be really hot in here and you don't know what to do with yourself." E11*

There was a gas fire in E11, although the occupant rarely used it. She explained that this is because she cannot afford to do so, as she already spends around a quarter of her income (state pension) on bills. She does not use the second bedroom in her home because it is "bitterly cold" and she cannot afford to heat it.

> *"I don't put the fire on because of the extra expense. I got a letter [from the electricity supplier] two months ago and they were putting up my payments from £49 a month to £90 a month because I was in arrears. I've never been in arrears before but last year it was so cold the heating had to be on all the time." E11*

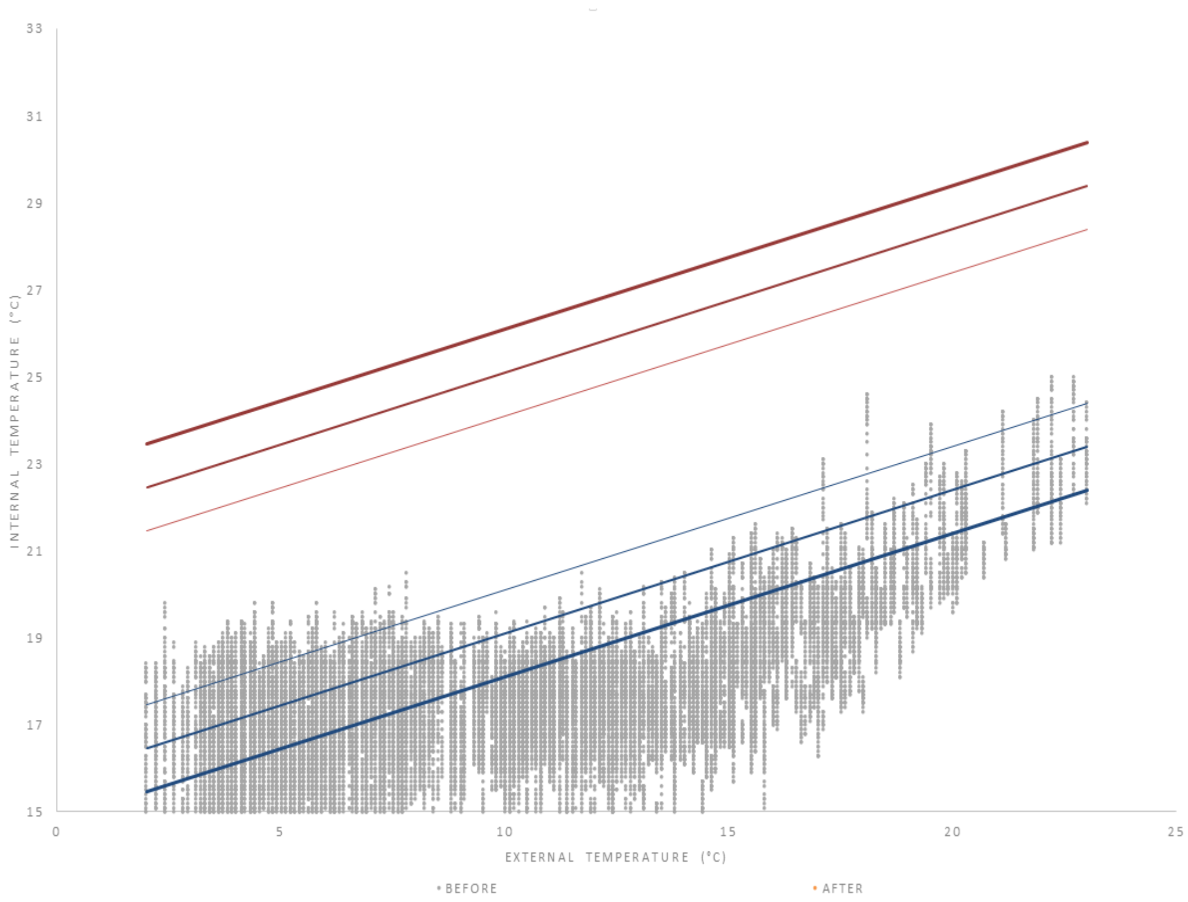

Figure 7-12 Dwelling E-11 thermal comfort assessment (Bold outer-most lines show category 3, with categories 2 and 1 the respectively less bold lines)

In contrast Figure 7-13 suggests the possibility of discomfort due to overheating in the winter months at times, possibly because the dwelling is vulnerable to high incidental gains (e.g. solar gains) or else it may be an indication that the occupant prefers a warm environment and is prepared to accept the cost of achieving this. This also shows that the retrofit has not altered the occupants' behaviour and they are still heating their home to higher temperatures to some extent. In these instances, the retrofit's potential for financial savings would be high since the costs of achieving the high set point would be reduced and no additional comfort taking would be anticipated.

Again, data from the interviews provide insight into the temperature profile. The family have three young children, one with a disability, and they prefer to heat their home to a warmer temperature. Since the retrofit they talked about how they keep their heating on for less time while maintaining their preferred temperature.

> *"We like to keep it reasonably warm for the kids and I like to be warm…. My disabled child's immune system doesn't work properly so like if he gets poorly he gets it bad. And then the youngest one, he's got bronchitis." E25, pre-retrofit*
>
> *"I used to put the heating on in a morning and didn't' turn it off until we went to bed. Now I turn it on in the morning for about 45 minutes and we put it on about 20 minutes before the kids come home from school." E25, post-retrofit*

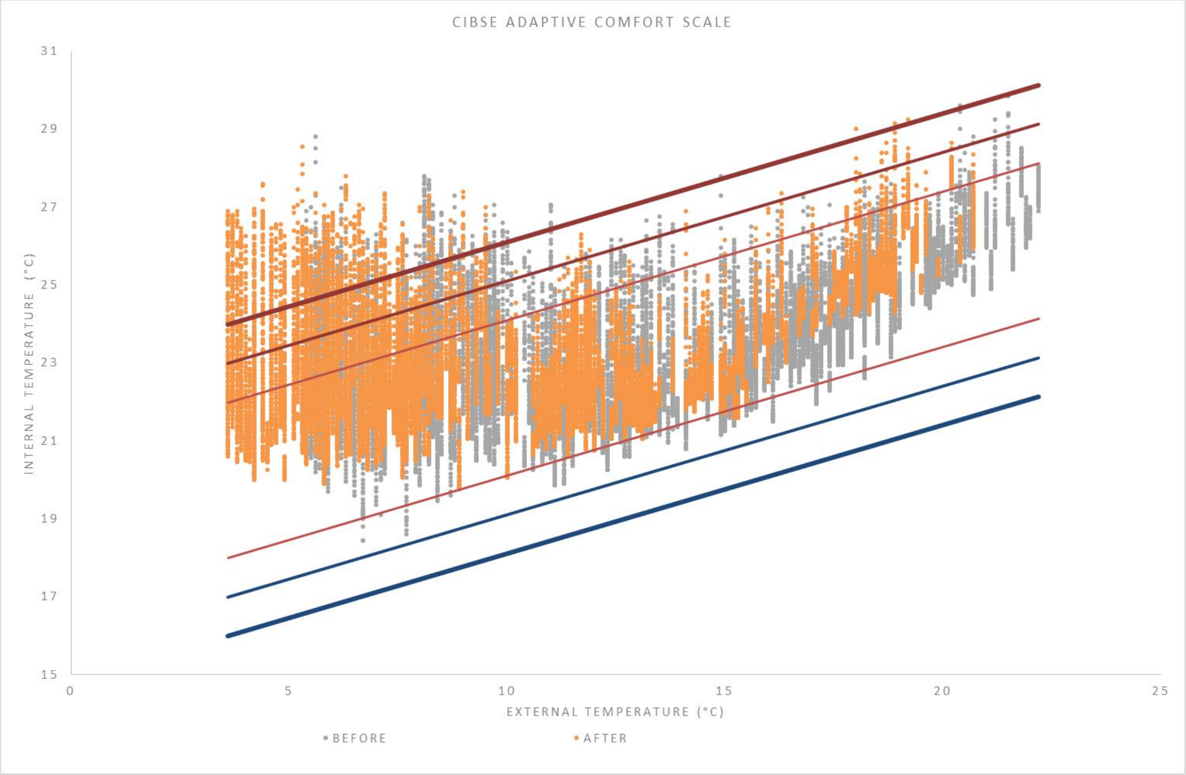

Figure 7-13 Dwelling E-25 thermal comfort assessment

Figure 7-14, shows a Dwelling E-16 which achieves comfort both before and after the retrofit which may indicate no noticeable comfort taking. The retrofit for Dwelling E-16 may therefore appear relatively more successful than in dwellings where there was a degree of comfort taking. In order to assess the influence of thermal comfort on the success of the retrofit it is therefore necessary to investigation the fuel cost reductions of each dwelling in conjunction with the perceived comfort taking. The occupant reported that her home stays warmer for longer, and while she doesn't monitor her fuel bills (as they are online rather than posted to her), she expects that the bills are lower post-retrofit.

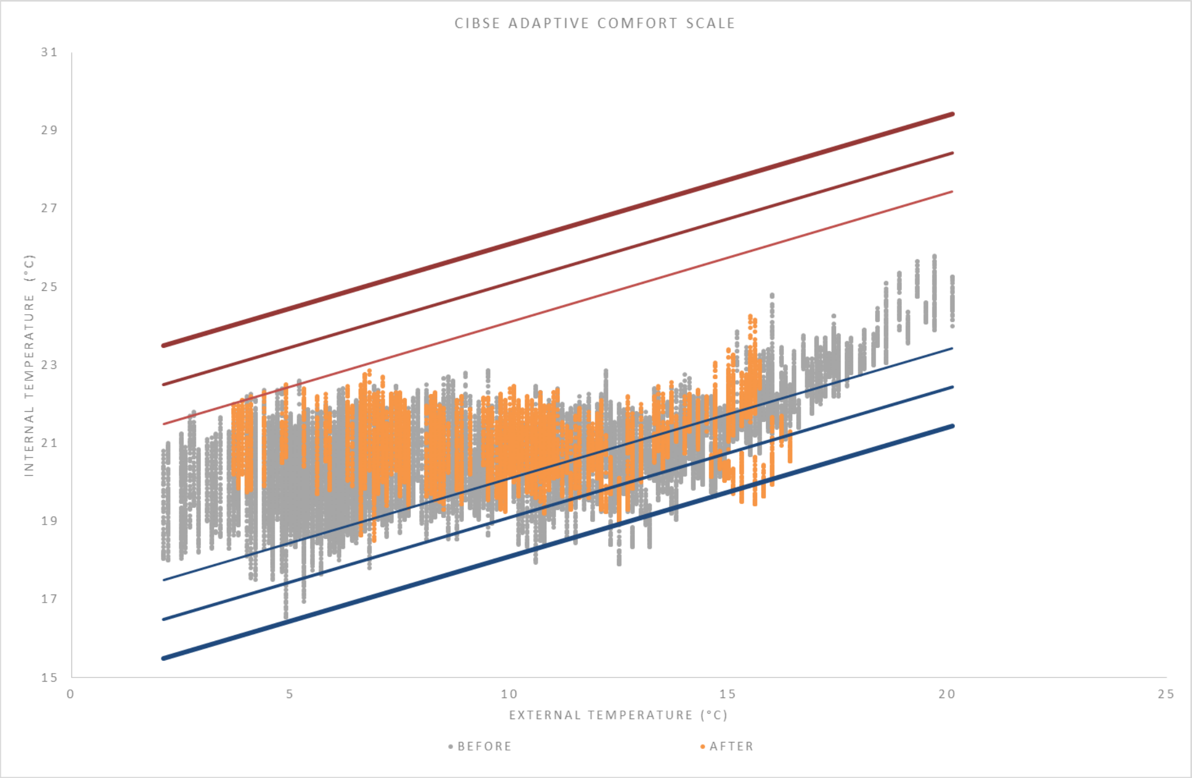

Figure 7-14 Dwelling E-16 thermal comfort assessment

Unfortunately, as previously stated owing to complications encountered during this project it was not possible to collect before and after data for all the dwellings. Figure 7-15 has an acceptable period of both before and after data and we can see that during the period before the retrofit took place the internal temperatures were below the comfort threshold, but afterwards they are above it and within the acceptable temperature range. In addition, in this particular instance the occupant lived and slept in one room prior to the retrofit and post intervention was using the bedroom again. This may represent a success in terms of the outcome of a retrofit from the point of view of thermal comfort. As stated, however, comfort data alone is only half of the story and it is important to also check the scale of reduction of the cost of providing this comfort in order to have a holistic understanding of success. As explored later in the report, the fuel bills for E-34 were substantially lower post-retrofit. Some 18 months following the retrofit she reported being £800 in credit with her energy provider.

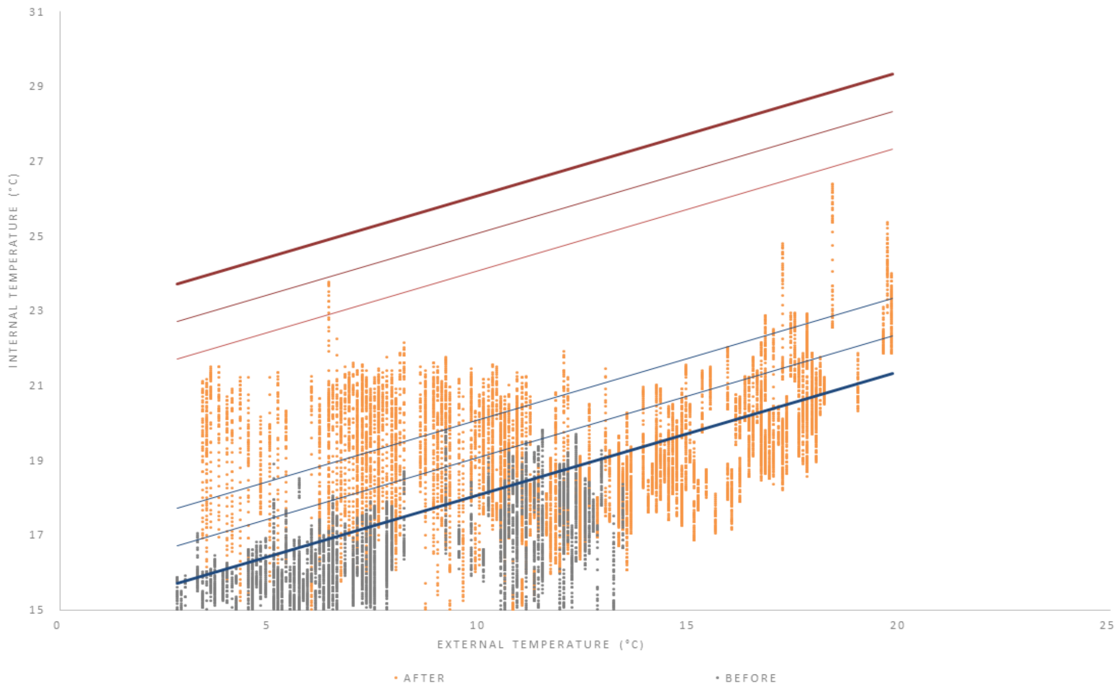

Figure 7-15 Dwelling E-34 thermal comfort assessment

7.6.3 Other considerations on thermal comfort and comfort taking

There are some additional assessment methods that may provide further insight into thermal comfort and comfort taking observed. Table 7-1 shows the type of retrofit and the influence on comfort although it is not possible to identify if there are any difference in comfort taking between EWI and IWI.

There are also considerations around whether the more comfortable average daily temperatures achieved were a result of having higher set points or of the property remaining warm for longer as a result of the retrofit reducing the heat loss from the property after the heating has shut off for the day. This assessment will provide more evidence to explain how much comfort taking is a deliberate activity and if higher comfort levels are achieved as a result of the insulation or as a result of increased fuel use.

7.7 Energy data assumptions; domestic hot water and electricity

In order to compare the effectiveness of the retrofits on the dwelling energy efficiency we used the following four metrics 1) PGT, 2) HDD, 3) DHD and 4) HDG and compared these to the observed energy consumption. In order to do this, we first made two additional steps; 1) to attempt to omit non-space heating energy and 2) to completely remove all electricity (except in the case of PGT).

For step 1 the rationale for removing the non-space heating energy i.e. the domestic hot water (DHW) is simply that this energy use is not directly related to the energy efficiency of the dwelling (although may have some residual impact) and may therefore skew the heating energy consumption.

It was not in the scope of the project to measure directly the amount of DHW used in each dwelling. However, it is possible to make some reasonable assumptions regarding this from the data collected. We estimated the amount of DHW demand by analysing the average daily energy use on days where external temperatures exceeded 21°C at which times it could reasonably be assumed that any heating energy must be DHW only. Thus, average values for DHW per half hour could be calculated, specifically for each house, and removed from each day’s heating energy use. This method of establishing a base energy load is described by Fels (1986).

With regard to step 2, all but three homes had gas as the main space heating fuel. In these homes all electricity use in the dwellings, within the thermal envelope of the building can be assumed to ultimately decay into heat; apart from that which escapes as light and sound or which is used to charge mobile devices used outside the dwelling. It is noted that electricity, which escapes as light or sound, is likely to be a very small proportion of household energy consumption. When undertaking heat loss calculations it is important to capture all this energy, as in the case for the PTG. However, when reporting on improvements made from energy efficiency retrofits the influence on the heating energy use or fuel bills is perhaps more important in terms of telling a story, especially to home owners and RSLs. In addition, since the electrical energy used before and after the retrofit is likely to be similar, the decision was made to remove all of the non-space heating electricity from the HDD calculations, DHD and HDG.

In the three electric only dwellings (E-21, E-22 and E-23) all the electricity use remaining after extracting the DHW consumption was assumed to be providing space heating and therefore these may appear to be more energy intensive dwellings.

7.8 Results of the energy efficiency retrofit

Each building has a retrofit performance sheet summary sheet in Appendix I, which provides a narrative of the dwelling energy performance characteristics, its response to the retrofit and the quality of the in use data available. These are useful for gaining a more holistic understanding of the project and its findings, especially with regard to the uncertainty of some of the data sets. This section attempts to describe the aggregate findings from the project as a whole.

To consider the benefit of each retrofit in this project it is worth first considering benchmark data on the effectiveness of previous energy efficient retrofits projects. Reductions in gas consumption as a result of historical government insulation schemes have been demonstrated to be successful in large high level data sets for example via the Housing Energy Efficiency Database (HEED). A summary of these data is shown in Figure 7-16 (DECC, 2015) which identifies that improvements between around 2% and 17% may be achieved depending on the type of insulation measure installed. The Energy Follow Up Survey (EFUS) results suggest that there is no statistically significant difference in gas consumption rate in dwellings with or without loft or wall insulation, although there is a significant difference between those with or without double glazing (BRE, 2013).

In this project we are mostly concerned with solid wall insulation (EWI and IWI) for which the mean predicted saving in fuel bills is shown to be around 15% according to the National Energy Efficiency Data-Framework (NEED); however, the spread around the mean can be large.

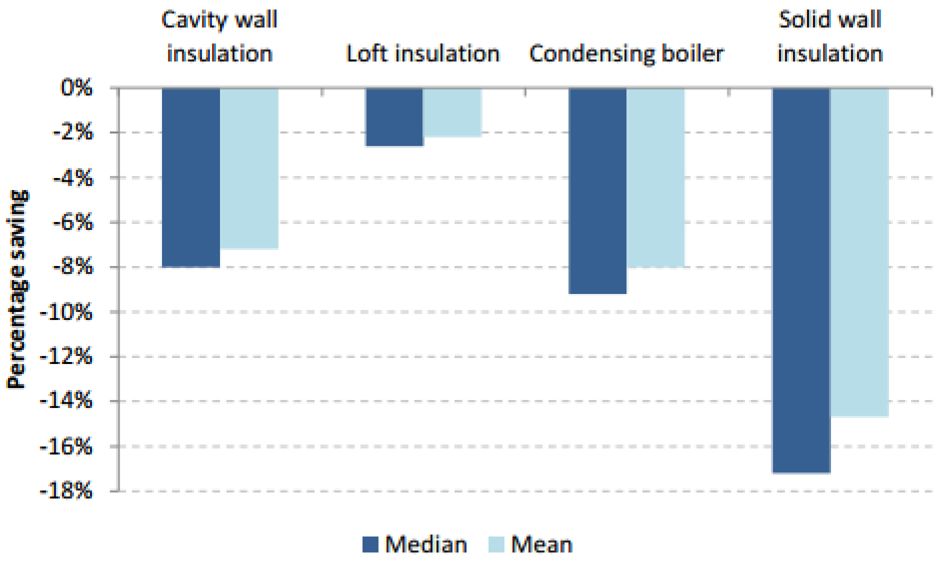

Figure 7-16 NEED gas consumption reductions from retrofits (sourced from DECC, 2015)

7.8.1 Summary of monitoring results

This project which has a much smaller sample size than the EFUS survey and cannot therefore be scaled up to a national level. However, this project does provide more detailed data on the individual dwellings and so it may be able to provide a greater insight into the causes of relative levels of success.

The following sections provide detail on the four different analysis methods outlined; however, the results are first summarised here. Table 7-2 presents an overview of the retrofit improvement that has been measured according to the four analysis methods identified. It excludes homes for which we have either only before or only after data. It also removes those dwellings for the assessment which had either a very weak relationship in the PTG and HDG (r^2 lower than 0.4) and also considers only those homes with a greater than 150 DHD or HDD worth of data.

Table 7-2 Average change in energy consumption achieved by retrofit

Analysis method		Mean % change
Power Temperature Gradient (PTG)	n=11	-28%
kWh / Heating Degree Day (HDD)	n=18	-4%
kWh / Dwelling Heating Demand (DHD)	n=18	-20%
Heating Demand Gradient (HDG)	n=13	-29%

The data from this project suggests that an average improvement in energy efficiency in the region of 4% to 29% may have been achieved by the retrofits. This is in line with or possibly slightly more than the average improvement previously identified by NEED. Analysis using a Two-sample t-test shows the difference between the before and after energy efficiency is not statistically significant. However, this may be expected owing to the small sample size and the heterogeneity of energy behaviour observed in the homes. These average values quoted therefore hide a large degree of variability in the results. In addition, the sample sizes on which these conclusions are drawn are small.

Figure 7-17 shows the variation in savings including some dwellings that used more energy following the retrofit. Specifically, there are several dwellings where a large increase in energy consumption has been observed after retrofit, this may have be caused by a change in dwelling circumstance and heating behaviour, an error in the sensors and data collection or else represent a failure of the retrofit. The interview data provide insight into some of the dwellings in which there is an increase in energy consumption. For example, E17 switched their energy supplier and tariff so one that, for their family, was substantially cheaper. So even though they did not have EWI/IWI installed, their energy bills were lower despite their consumption increasing.

In addition, there were sixteen dwellings where secondary heating was observed, other than central heating. Some secondary heating sources were gas fires which would be captured in the gas consumption data, although these have a significantly different heat delivery efficiency when compared to central heating via gas boiler and radiators. Other secondary heating systems observed included fan heaters, oil radiators, electric bar heaters and wood burning stoves which have the potential to significantly affect the energy analysis performed in this project; however, it was not always possible to identify when these secondary heating systems were being used.

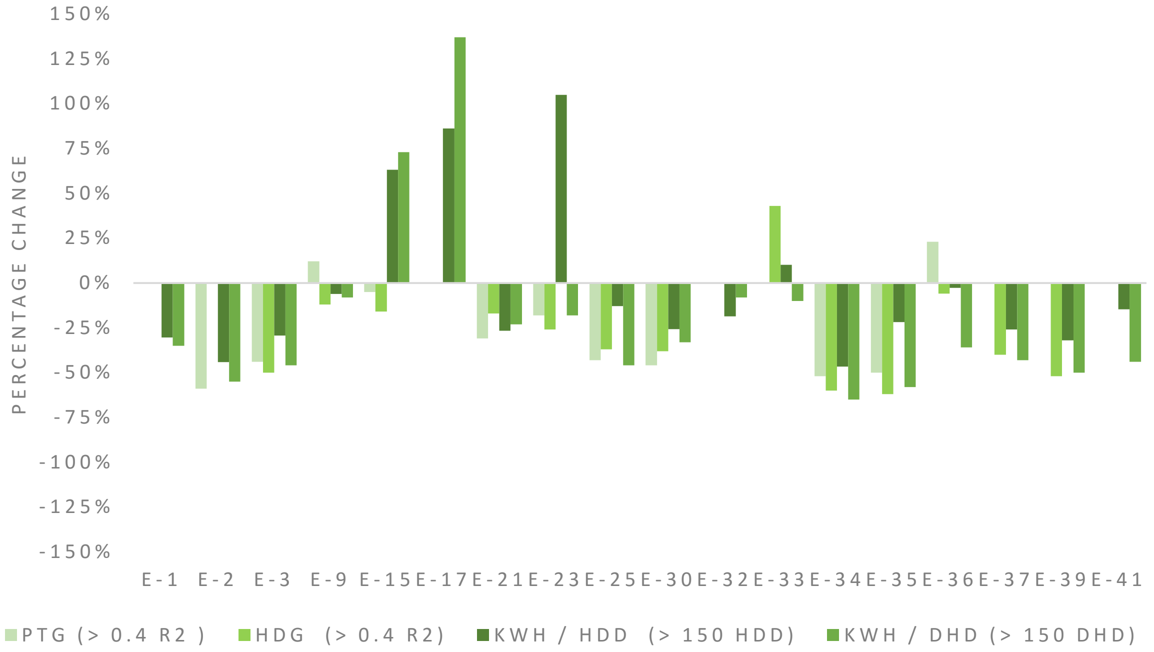

Figure 7-17 Summary of retrofit improvements

The relative improvements shown by each analysis method in Figure 7-17 are to some extent similar, however, there are some clear instances where one analysis method provides dramatically different results of the effectiveness of the retrofit. Thus, the analysis method by which the improvement in energy efficiency is calculated is important. This project does not recommend a preferred method since there are important benefits and limitations of each. The finding does imply that the ability of monitoring projects to reliably quantify the improvement of a retrofit is very sensitive to the quality of the monitoring data and the analysis technique chosen.

In generating these average improvement values twenty-nine of the forty-seven dwellings were rejected from the assessment owing to either their retrofit not taking place or unreliable data sources as previously described.

An alternative way to view the results is presented in Figure 7-18 which incorporates all the data collected irrespective of its reliability. This shows that although there's a great variation in the retrofit success, the majority of the dwellings did see improvements in their energy efficiency according to all analysis methods used.

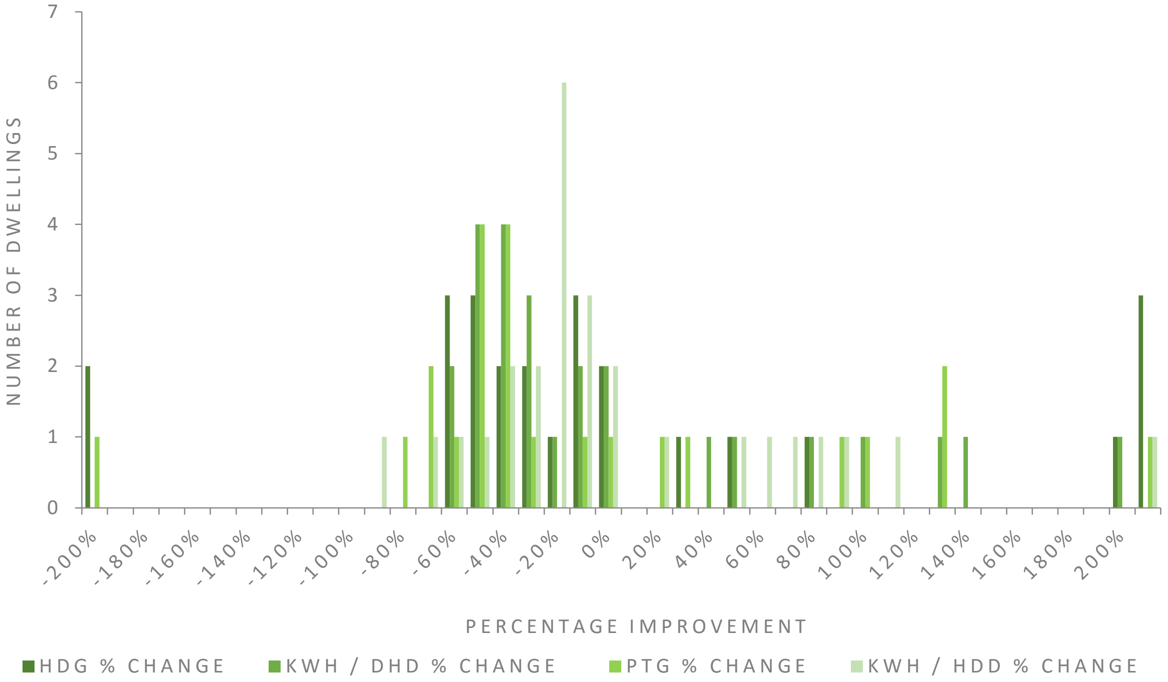

Figure 7-18 Retrofit impact on energy efficiency (a negative result represents an improvement)

The data for all the individual dwellings are presented and described in the dwelling retrofit performance sheets in Appendix I, however the following sections provide an overview of all the data for all the dwellings for each analysis method, highlighting the common findings as well as the degree of variation and uncertainty found.

7.8.2 PTG

The PGT is essentially the gradient of the line of best fit and thus its value is equal to the change in the y axis (energy in kWh/m^2) relative to a change of 1 unit on the x axis (external temperature in °C). A negative value represents a reduction in energy use when external temperature increases which is expected.

An example PGT is shown in Figure 7-19 where it can be seen that less heating energy is used in the winter after the retrofit. An understanding of the internal temperatures is required to ensure this is not simply indicative of lower temperatures in the dwelling; in this instance this is not the case and the savings can be assumed to be due to the retrofit. The data are not perfectly clustered however, highlighting the heterogeneous energy consumption of dwellings. The r^2, which is a measure of the explanatory power of the trend, suggests that external temperature is responsible for 81% of the total power used by the dwelling before the retrofit but only 65% afterwards. Thus even where a relatively strong relationship exists a substantial amount of energy use is not related to keeping the property warm.

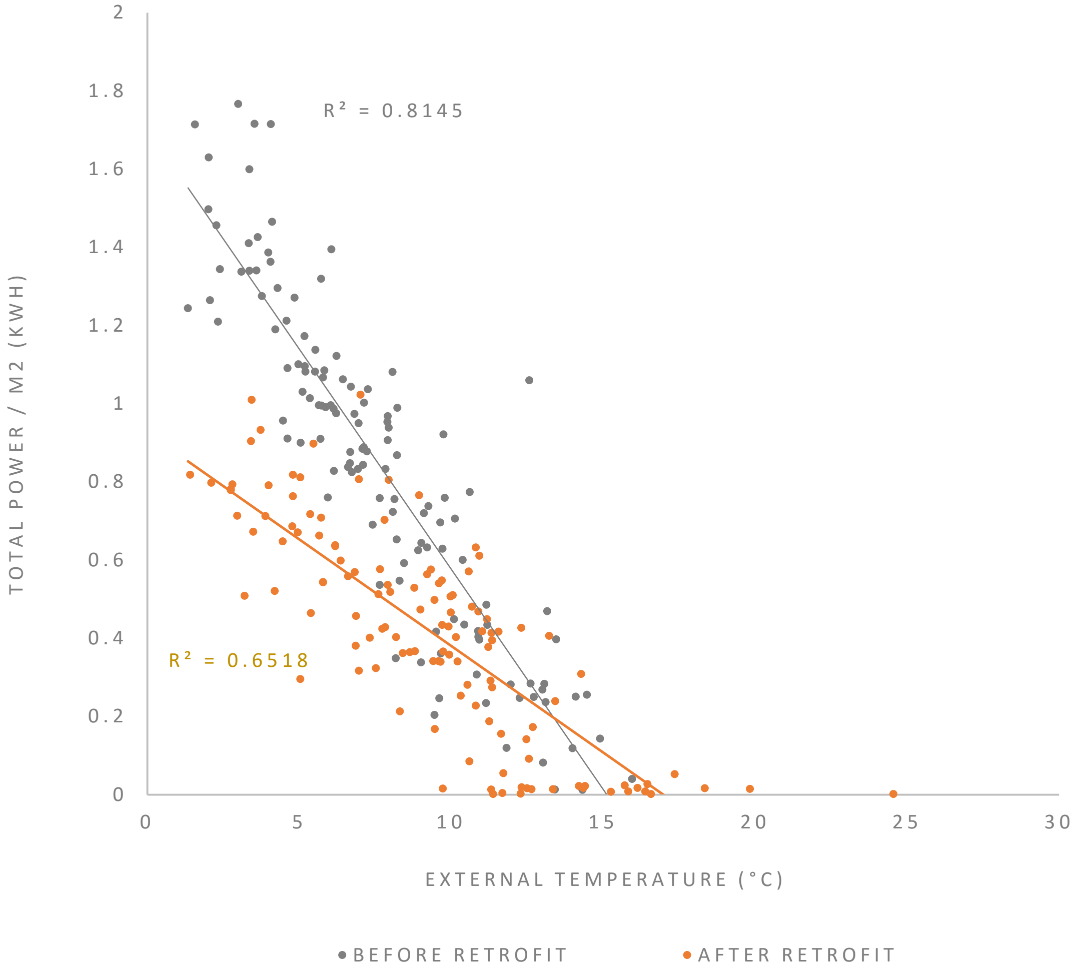

Figure 7-19 Dwelling E34 PTG

A summary of the PGT calculations can be seen in Table 7-3. There are several dwellings for which it was possible to calculate a before and after PTG. Some of these were extreme outliers, especially those where the r^2 was below 0.4. These anomalous readings may be due to the timing of installing equipment (i.e. insufficient before or after periods) or alternatively may be due to sensors failing, or being moved, or may simply be a reflection of the occupant altering their heating behaviour.

Table 7-3 Summary of PTG for all dwellings

Dwelling ID	PTG Before (r^2)	PTG After (r^2)	% Change
E-1	-0.02 (0.07)	-0.05 (0.81)	92%
E-2	-0.03 (0.65)	-0.01 (0.48)	-59%
E-3	-0.03 (0.54)	-0.01 (0.47)	-44%
E-4	-	-	-
E-5	-	-0.02 (0.63)	-
E-6	-	-	-
E-7	-	-0.04 (0.65)	-
E-8	-	-	-
E-9	-0.066 (0.74)	-0.074 (0.72)	12%
E-10	0.02 (0.49)	-	-
E-11	-0.001 (0.01)	-	-
E-12	0.001 (0.001)	-	-
E-13	-0.08 (0.78)	-	-
E-14	0.002 (0.03)	-	-
E-15	-0.06 (0.67)	-0.05 (0.47)	-5%
E-16	-0.06 (0.67)	-	-
E-17	-0.003 (0.21)	-0.01 (0.37)	86%
E-18	-0.0009 (0.045)	-0.002 (0.09)	130%
E-19	-0.001 (0.005)	-	-
E-20	-0.05 (0.58)	-	-
E-21	-0.06 (0.66)	-0.04 (0.63)	-31%
E-22	0.01 (0.01)	-0.08 (0.68)	-702%
E-23	-0.031 (0.53)	-0.026 (0.60)	-18%
E-24	-	-0.001 (0.19)	-
E-25	-0.04 (0.58)	-0.02 (0.41)	-43%
E-26	-0.02 (0.88)	-	-
E-27	-0.35 (0.03)	-	-
E-28	-	-	-
E-29	-0.01 (0.14)	-0.03 (0.60)	222%
E-30	-0.05 (0.46)	-0.03 (0.71)	-46%
E-31	-0.0003 (0.14)	-0.0001 (0.03)	-58%
E-32	-0.04 (0.20)	-0.09 (0.55)	130%
E-33	-0.06 (0.55)	-0.02 (0.39)	-70%
E-34	-0.11 (0.81)	-0.05 (0.65)	-52%
E-35	-0.06 (0.40)	-0.03 (0.45)	-50%
E-36	-0.025 (0.46)	-0.031 (0.55)	23%
E-37	-	-	-
E-38	-0.07 (0.23)	-	-
E-39	-0.05 (0.33)	-0.02 (0.54)	-61%
E-40	-0.05 (0.15)	-0.01 (0.03)	-84%
E-41	-0.06 (0.10)	-0.02 (0.12)	-71%
E-42	-	-	-
E-43	-	-	-
E-44	-0.02 (0.04)	-0.01 (0.26)	-42%
E-45	-	-	-
E-46	-	0.0001 (0.001)	-
E-47	-	-	-

7.8.3 HDD

HDD are a well-accepted method of characterising average heating energy demand for particular locations. For this reason, the calculation was included in our analysis to understand what results a conventional analysis of the data might yield.

Table 7-4 Summary of energy use per HDD for all dwellings

Dwelling ID	kWh/m^2/HDD Before	kWh/m^2/HDD After	% Improvement
E-1	0.07	0.05	-30%
E-2	0.02	0.01	-44%
E-3	0.03	0.02	-29%
E-4	-	-	-
E-5	0.01	0.02	43%
E-6	-	-	-
E-7	0.03	0.05	73%
E-8	-	-	-
E-9	0.08	0.08	-6%
E-10	0.02	-	-
E-11	-	-	-
E-12	0.03	-	-
E-13	0.10	-	-
E-14	-	-	-
E-15	0.07	0.12	63%
E-16	0.09	-	-
E-17	0.01	0.01	86%
E-18	0.01	0.00	-22%
E-19	-	-	-
E-20	0.08	-	-
E-21	0.07	0.05	-27%
E-22	0.04	0.09	105%
E-23	0.04	0.04	-13%
E-24	-	-	-
E-25	0.06	0.03	-52%
E-26	0.03	-	-
E-27	0.66	-	-
E-28	-	-	-
E-29	0.39	0.04	-90%
E-30	0.05	0.04	-26%
E-31	0.00	0.00	248%
E-32	0.12	0.10	-19%
E-33	0.02	0.02	10%
E-34	0.11	0.06	-47%
E-35	0.06	0.05	-22%
E-36	0.08	0.08	-3%
E-37	0.03	0.02	-26%
E-38	0.08	-	-
E-39	0.04	0.03	-32%
E-40	0.03	0.04	52%
E-41	0.07	0.06	-15%
E-42	0.02	0.00	-78%
E-43	0.00	-	-
E-44	0.02	0.01	-60%
E-45	-	-	-
E-46	-	-	-
E-47	-	-	-

7.8.4 DHD

By comparing the results of the HDD analysis and the DHD analysis we have attempted to try to understand the influence of the occupant decisions around heating hours and heating set points. The HDD data do not account for these variations and so may be under or overestimating the energy efficiency of the dwellings. The DHD analysis shown in Table 7-5 addresses this by reducing the number of assumptions in the calculation procedure.

Table 7-5 Summary of energy use per DHD for all dwellings

Dwelling ID	kWh / DHD / m^2 Before	kWh / DHD / m^2 After	% Change in heating energy
E-01	0.06	0.04	-35%
E-02	0.02	0.01	-55%
E-03	0.04	0.02	-46%
E-04	-	-	-
E-05	-	0.01	-
E-06	-	-	-
E-07	0.01	0.04	199%
E-08	-	-	-
E-09	0.08	0.07	-8%
E-10	0.01	-	-
E-11	-	-	-
E-12	0.04	-	-
E-13	0.07	-	-
E-14	-	-	-
E-15	0.06	0.10	73%
E-16	0.07	-	-
E-17	0.006	0.013	137%
E-18	0.01	0.03	129%
E-19	-	-	-
E-20	0.06	-	-
E-21	0.06	0.04	-23%
E-22	0.05	0.07	40%
E-23	0.04	0.03	-18%
E-24	-	-	-
E-25	0.03	0.02	-46%
E-26	0.03	-	-
E-27	0.59	-	-
E-28	-	-	-
E-29	0.02	0.04	49%
E-30	0.05	0.03	-33%
E-31	0.0004	0.0008	93%
E-32	0.10	0.09	-8%
E-33	0.028	0.025	-10%
E-34	0.14	0.05	-65%
E-35	0.08	0.03	-58%
E-36	0.07	0.04	-36%
E-37	0.04	0.02	-43%
E-38	0.12	-	-
E-39	0.04	0.02	-50%
E-40	0.13	0.07	-50%
E-41	0.08	0.04	-44%
E-42	-	-	-
E-43	0.005	-	-
E-44	0.04	0.01	-65%
E-45	-	-	-
E-46	-	-	-
E-47	-	-	-

Similarly, to the HDD calculations the total DHD is calculated and the total space heating energy use over the same time period is also calculated. From this we can understand the energy needed to provide a DHD of space heating; the results are presented in Table 7-5 for each dwelling where a negative change represents an improvement in energy efficiency.

7.8.5 HDG

The HDG is the gradient of the line of best fit produced by plotting the heating energy use (kWh space heating) against the heating demand, DHD for each day. An example of this is shown in Figure 7-20 where the reduction in energy needed to provide heating can clearly be seen as the after data is below the before data. In this instance there is a relatively good relationship showing that the heating demand (DHD) is able to explain over 80% of the space heating energy consumption (kWh/m^2). In contrast to the case of PTG, we can assume that the improvement in energy efficiency is due to the retrofit rather than a reduction in the set points since internal temperatures are a function of the DHD. The after data is remarkable in being substantially below the before data; the comparison is much clearer than the equivalent PTG for the same house, although this is not always the case.

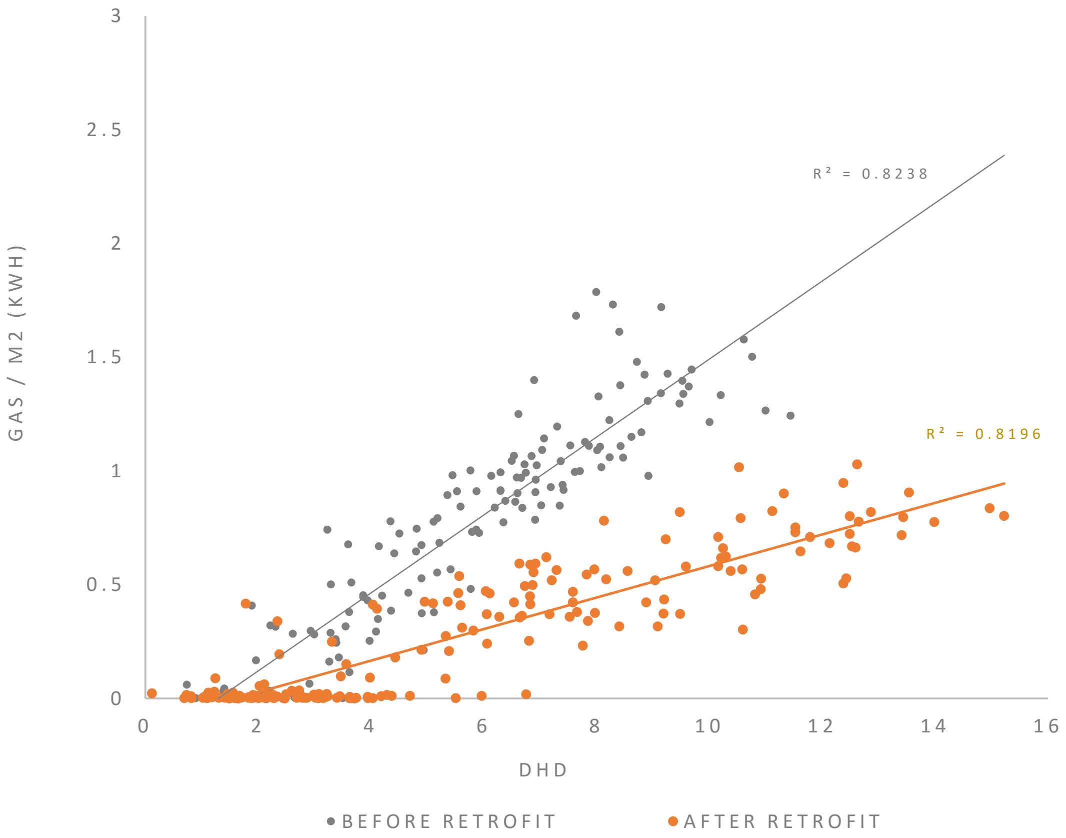

Figure 7-20 HDG for dwelling E-34

Individual HDG values for each dwelling have been calculated as in Figure 7-20 and the results are summarised in Table 7-6. As can be seen, similarly to the PGT there are several dwellings for which there was a very poor relationship between the space heating energy consumption and the DHD and for which an unreliable or uncertain HDG has been calculated. Those dwellings that had no before or after HDG or where there was uncertainty in the quality of the data (r^2 below 0.4) were not included in the overall summary analysis although they have been included in Table 7-6 so that they can be identified.

Table 7-6 Summary of HDG for all dwellings

Dwelling ID	HDG Before (r^2)	HDG After (r^2)	% Change
E-1	0.04 (0.18)	0.05 (0.82)	30%
E-2	0.0097 (0.18)	0.0095 (0.47)	-2%
E-3	0.05 (0.57)	0.02 (0.57)	-50%
E-4	-	-	-
E-5	-	0.01 (0.62)	-
E-6	-	-	-
E-7	0.004 (0.07)	0.05 (0.76)	963%
E-8	-	-	-
E-9	0.10 (0.85)	0.09 (0.79)	-12%
E-10	0.02 (0.7)	-	-
E-11	-	-	-
E-12	0.04 (0.04)	-	-
E-13	0.08 (0.81)	-	-
E-14	-	-	-
E-15	0.07 (0.73)	0.06 (0.58)	-16%
E-16	0.07 (0.63)	-	-
E-17	0.003 (0.38)	0.006 (0.69)	74%
E-18	0.001 (0.02)	0.005 (0.07)	261%
E-19	-	-	-
E-20	0.05 (0.57)	-	-
E-21	0.07 (0.49)	0.06 (0.68)	-17%
E-22	-0.004 (0.001)	0.09 (0.68)	-2226%
E-23	0.05 (0.50)	0.03 (0.53)	-26%
E-24	-	-	-
E-25	0.05 (0.65)	0.03 (0.53)	-37%
E-26	0.04 (0.81)	-	-
E-27	0.4 (0.04)	-	-
E-28	-	-	-
E-29	0.01 (0.02)	0.04 (0.65)	391%
E-30	0.05 (0.50)	0.03 (0.67)	-38%
E-31	-0.0001 (0.005)	0.0001 (0.0014)	-215%
E-32	0.04 (0.2)	0.11 (0.56)	194%
E-33	0.02 (0.25)	0.03 (0.39)	43%
E-34	0.17 (0.82)	0.07 (0.82)	-60%
E-35	0.12 (0.54)	0.05 (0.56)	-62%
E-36	0.039 (0.52)	0.037 (0.48)	-6%
E-37	0.04 (0.58)	0.03 (0.73)	-40%
E-38	0.11 (0.53)	-	-
E-39	0.05 (0.59)	0.02 (0.65)	-52%
E-40	0.06 (0.15)	0.03 (0.04)	-60%
E-41	0.08 (0.32)	0.04 (0.20)	-56%
E-42	-	-	-
E-43	0.01 (0.66)	-	-
E-44	0.04 (0.17)	0.01 (0.34)	-42%
E-45	-	-	-
E-46	-	0.001 (0.06)	-
E-47	-	-	-

7.9 Future analysis methods

It will be interesting to explore the differences between the PTG and HDG as well as the HDD and DHD analysis methods.

Further analysis of the before and after data sets collected may establish if the differences found are statistically significant and will be a useful exercise; however, given the number of variables that influence energy use any correlation may be weak.

To further explore the data collected several more analytical practices will be undertaken. There will be a synthesis of the data relative to the building survey and occupant interview data to understand any relationships that can be established regarding building form and occupant characteristics. Investigating the heating hours of dwellings and their relative energy intensity will identify if the comfort taking potentially identified is a result of higher set points in dwellings or due to dwellings staying warm for longer

An additional analysis method for establishing the percentage reduction in fuel bills will be investigated that uses neural networks to model the relationships between input variables to fill in the blanks of the missing data and provide more robustness in the claims and quantification of improvements made.

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8 Occupant behaviour study

8.1 Background

The Green Deal was an innovative government finance scheme in which home owners receive energy efficiency improvements to their homes and then paid for them over a period of time through savings in their fuel bills. The upfront costs of improvements are met by organisations, which are repaid over time as homeowners recoup the cost through savings in their energy bills. A diverse range of improvements qualify under the scheme and each home must first be assessed in order to ensure that the improvements will lead to significant increases in energy efficiency. A key feature of the Green Deal is that the expected energy savings must be greater than the cost of the improvements. While the government has suspended the scheme, it is expected that similar pay back systems will be used by others and the results presented are still relevant to inform future finance schemes.

Because the success of the scheme is based both on energy efficiency improvements and residents' energy use it is also valuable to understand how improving energy efficiency affects residents' decisions around energy use and their experiences of living in their homes. This includes the ways in which they use and heat their homes and the impact of having a warmer home on their health and their quality of life. Warmer living conditions can help to address the large health inequalities that residents in deprived areas face but in the Green Deal residents need to save money through the improved energy efficiency of their home rather than use the financial savings made to keep their home warm or warmer than it needs to be. It is important, therefore, to understand the way in which residents think about the Green Deal and the decisions they make about the way in which they heat their home. This includes exploring their willingness to heat their homes to a comfortable level while making the necessary financial saving. This financial saving is the premise upon which the Green Deal is offered.

At present there is a current lack of research into how residents' behaviours alter following improvements to the energy efficiency of their homes. When the estimated financial savings are not realised it is difficult to identify how much is due to a lower-than-expected energy efficiency improvement and how much is due to changes in the ways in which residents use and heat their homes. It is thought that financial savings can be eroded by "comfort taking", i.e. residents keeping their home much warmer than it was previously, either because they now believe they can afford to do so, or because the improved insulation means that their home is newly capable of heating up to and maintaining the desired temperature. The current research will start to explore how and why residents change their energy use behaviour and how they use their homes. The results can be used to inform future policy and also a future larger scale project on in-use behaviour. They could also be used to provide future Green Deal households with information that will help influence their attitudes towards energy use and thereby help them to keep their home warm without eroding the financial savings required to pay back the Green Deal investment.

8.2 Theoretical framework

Because we wish to understand behaviour and what drives it we need to use a behavioural framework that includes both psychological and social components. We have used a social cognitive framework to measure, explore and understand the factors that predict energy use. This framework highlights the importance of what people think (their cognitions), which forms the basis of their attitudes towards energy use. It also highlights the importance of social influences: beliefs about what other people expect them to do (their social norms); and what they think they should be doing with regards energy use (their moral norms). Finally, the framework also includes people's confidence that they could reduce their energy bills if they wanted to (their self-efficacy) and their intentions to reduce energy use in the future. We had intended to take into account temporal discounting, i.e. perceptions of the difference between short-term gains (a warmer house) versus long-term losses (not paying off the Green Deal loan). This theory suggests that people will give greater weight to benefits that they experience in the short-term, i.e. a warmer house, and lesser weight to losses that they will not experience for some time, i.e. not being able to pay off the Green Deal loan. However, as only one of our participants had taken a loan to pay for their insulation and only three made a financial contribution, this was not included in the interviews and instead it will be explored during the focus groups.

8.3 Methods

Because of the lack of existing knowledge on resident energy use following Green Deal improvements we used a qualitative approach which provided depth of understanding of residents' experiences of having a more energy efficient home, including how the improvements influenced their decisions about energy use as well as the effect of improved energy efficiency on their health and quality of life. The research was based on semi-structured interviews, which provide the flexibility to explore unanticipated aspects of residents' experiences that arise during the conversation. This was supplemented by focus groups and a brief survey on thermal comfort. Initially we had planned a small diary study in which some participants were to keep a log of their heating use over part of the winter heating period. However, due to slow recruitment, and residents' reluctance to commit to this prolonged aspect of the study, the diaries were not completed. Instead, the interview topic guides were adapted to incorporate this aspect of the study.

All the households who were identified and agreed to take part in the monitoring project were also asked if they would like to take part in the interviews, though not all consented. One occupant (E-00) was included in the behaviour study but could not be included in the monitoring study because their gas meter was incompatible.

8.3.1 Interviews

We conducted semi-structured depth interviews with 31 residents at one or more of three different time points:

- T1: before the insulation;
- T2: after the insulation had been installed but before the first bill showing energy savings and loan costs;
- T3: at least a year after the insulation had been installed and after a winter period.

Interviews took place in residents' homes and lasted around 45 minutes. Participants received a £20 incentive for taking part in each interview. By conducting a series of interviews with the same residents we were able to better understand the way in which they used their homes and any changes following the insulation.

The interviews explored the following points and the three topic guides are shown in Appendix J, K, and L

- Expectations about the changes a better insulated house would achieve.
- How the improvements have influenced perceptions of energy efficiency.
- The extent to which the improvements resulted in the anticipated benefits (both financial and comfort);
- Why people used more or less energy after the insulation was installed.
- Any changes in residents' experience of living in their home.
- How and why any wider benefits (such as health benefits) have occurred.

The interviews included a design walk-though in which residents walked through their homes with the researcher to talk about any differences they anticipated or noticed, and parts of their home that feel particularly cold and what they do to manage the temperature in their home. Interviews were audio recorded and transcribed verbatim.

8.3.2 Survey

The survey comprised a series of questions to measure thermal comfort, with questionnaire items supplied by Professor Swan of the University of Salford, as recommended by DECC. In addition, a single-item health measure adapted from the EuroQol EQ5D was included. The survey is shown in Appendix M.

8.3.3 Participants

Table 8-1 contains details of the participants who took part in the interviews and surveys, including the time points at which data were collected, who lives in the home, any health problems the occupants were experiencing that might be affected by their living conditions, and any changes that occurred over the course of the research. Time 1 (T1) interviews took place before the insulation had been installed, Time 2 (T2) shortly after the installation, and Time 3 (T3) at least one heating season after installation. On occasion more than one interview was conducted during the same visit, such as a combined T1 and T2 interview (T1/T2).

Table 8-1 Details of participants in the behavioural study

Dwelling ID	Interviews	Occupants	Health Issues	Changes over study
E00	T1, T2	One adult male	No	No
E01	T1, T2, T3	Older couple	No	No
E02	T1, T2, T3	One adult and her teenage son	No	One additional adult living in the home.
E03	T1, T2, T3	Older couple	No	Retired and got a dog during the final year of the research.
E07	T1, T2	One adult and her four small children	No	Family moved away.
E08	T1, T2, T3	One adult, her adult son and two dogs	No	No
E09	T1	One adult, her three children and two cats	No	No
E10	T1	One adult, two adult children and one dog	Back pain and arthritis	Both children left home and one adult moved in.
E11	T1	One older adult	Frail and with heart problems	No
E12	T1	Two adults, two children	No	Family moved away.
E13	T1	Two adults, their adult son (part time) and pet birds and dogs	No	No
E14	T1	One adult and her adult daughter	Arthritis and asthma	Family moved away.
E15	T1, T2	Two adults, one adult son, three dogs and pet birds	High blood pressure and asthma	Adult son moved out.
E16	T1, T2, T3	One adult, and one cat	Asthma	One adult grandson stays two nights a week
E17	T1, T3	Two adults and one child	New baby in the home	Second child born.
E18	T1	Two adults: owner and lodger	No	Owner moved out, leaving one adult lodger.
E20	T1	Two adults and one adult son who lives in winter months.	No	No
E21	T1, T2, T3	Two adults	Arthritis	One adult retired, second adult retired during the research.
E22	T1, T2, T3	Two adults and one dog	COPD and Reynaud’s Disease	No
E23	T1, T2, T3	One adult, three children, three cats and one dog	No	One additional cat and one additional dog.
E24	T1/T2, T3	One adult	No	No
E25	T1/T2, T3	Two adults, three children and two cats	Children have poor immune system	No
E29	T1/T2	Two adults and three children	No	No
E33	T1, T3	One adult and (six weeks a year) a dog	No	Dog stopped visiting (Fan heater used to keep the dog warm)
E34	T1, T2, T3	One adult and one cat	Breathing difficulties	No
E35	T1, T2	One adult and one (part time) child	No	No
E36	T1, T2, T3	One adult	Diabetes, no sensation in legs and sensitive to cold	No
E39	T1/T2, T3	Two adults, two children, one dog	No	Changed energy provider.
E40	T1/T2	One adult	Arthritis and asthma	No
E43	T1	Two adults not yet living in the home	No	N/A
E45	T2, T3	One adult and one (part time) teenage grandson	No	No
E46	T3	One adult	No	No

8.3.4 Focus groups

We conducted a focus group with residents to explore their experiences of having external wall insulation, including the anticipated and experienced benefits, decisions around how much financial contribution they would be willing to make towards this and future schemes, and the impact of having the insulation on their general awareness of energy efficiency and interest in making further energy efficiency changes.

The focus groups took place at least 12 months after the insulation had been installed. It enabled participants to exchange and explore views and experiences. It included four participants and lasted around 90 minutes and each. participant received a £30 incentive for taking part.

8.3.5 Data analysis

Data from the interviews and focus groups were analysed thematically according to the methods of Braun and Clarke (2006). This qualitative approach provides a detailed understanding of the effect the improvements have made and why residents change (or do not change) how warm they keep their homes. Questionnaire data were analysed using descriptive and inferential statistics.

8.4 Results

The results of the behavioural study are presented in three sections. The first section summarises information from the interviews about how participants heat their homes and pay for their bills. The second section describes a thematic analysis of people’s expectations and experiences of living in a more energy efficient home. The third section presents the results of the survey and summarises information from the interviews on whether participants’ desired outcomes from their insulation had been met. This section also draws on monitoring data from Section 7.

8.4.1 How do participants heat their homes and pay their bills?

To better understand how participants heat their home before the insulation was installed, data were extracted from the interviews on how participants control the temperature in their home and how much they pay for energy bills. The results are summarised in Table 8-2.

Table 8-2 Controlling temperature and paying for energy bills before retrofit

	Room set point	Heating controls	Cost	Additional notes
E00	Not thermostatically controlled.	Timer: on an hour before he gets up and off 10 mins before he leaves for work. On again before he arrives home from work. On until midnight. TRVs on some of the radiators.	£68/month G&E	Fan heater and electric radiator used upstairs where there is no central heating.
E01	Thermostat set to 19	Heating on a timer, goes off at 11pm. If cold when it is off, turn it back on again.	£70/month G&E	Two oil heaters in the conservatory when it gets very cold.
E02	Thermostat set to 21	Heating on a timer, on early morning, off 10.30am, on again at 3pm, off at 10.30pm. Individual radiators turned off if rooms are too hot. Also TRVs.	£123/month G&E	Participant reports she needs to have the heating on in order to get hot water. Electric fan heater installed but not used because of the cost.
E03	Thermostat set to 24	Heating on a timer, on at 4.20am and off at about 6am. Turned on at 3.30pm for about an hour. No TRVs.	£109/month G&E	Doesn't set the thermostat to any particular temperature – turns it up high to turn heating on and turns it down low to turn heating off.
E07	N/A: heating either on or off.	Heating on a timer, on in morning, on between 2-4pm and again at 6-9pm. Has TRVs but doesn't know how to use them.	G&E varies, one quarter £200, next quarter £350	Central heating only recently installed. Was paying £150/week before then.
E08	Thermostat that used to be set to 21 but there was a fault so no longer used.	Heating on a timer, on at 5.30am and off at about 10am. On again 3-10pm. Son sometimes over-rides this and puts heating on earlier. TRVs used in individual rooms.	£110/month G&E	Doesn't know how to re-set the timer. Uses override to turn it on and off.
E09	Programmable timer sets temperatures for different periods of the day.	Timer controls temperature: increases in the morning before they get up, then down again before increasing again at 2.30pm and staying warm for the evening. Has TRVs.	£180/month G&E	Trying to reduce the bills because of a recent change in financial circumstances.
E10	Nothing in particular: Thermostat used to turn the heating on and off.	Central heating on a timer. Also has TRVs	£85/month G&E	Very draughty windows and poorly fitting doors means she has low expectations for how much of a difference EWI will make. Gas fires in the living room but try not to use them to avoid the extra cost. Two adult sons about to move out – they use a lot of electricity. Partner about to move in.
E11	Thermostat "clicker temperature dial" Previously on 20 but when cold it needs to be on 25.	No TRVs	Bills recently increased from £45/month to £90/month to repay arrears from last very cold winter.	House gets very cold in the winter. Also has a gas fire but rarely uses it because of the cost.
E12	Thermostat but doesn't set the temperature on it – turns heating on and off.	TRVs but they are not used. Thermostat used to turn heating on and off.	Doesn't know – husband deals with bills.	N/A
E13	Thermostat set to 18-20	Heating on a timer. 6am-?, then 6pm-7pm. Uses the boost function to give an additional hour of heating. TRVs	£120/month G&E	Has a heater to keep his pets warm.
E14	Thermostat but not used: manually turns central	Heating on a timer. ?-9.30am and 5pm-? TRVs.	£150/month G&E.	Income is £500/month so it is a struggle to pay. Has started to turn appliances off at the wall. Gas fire used in the winter. Had new

	heating on or off to over-ride timer.			windows and a new back door fitted the previous year which has improved things.
E15	Thermostat set to 20	Said the heating is on constantly but also said the timer is on 7am-12, 5pm-10pm.	£140/month G&E	Said it costs more to have the heating coming on and off than to have it on all the time. Home is occupied all day. Until recently had been on a pre-pay meter, which cost £240/month.
E16	Thermostat but doesn't set to 21	Thermostat. Unless having visitors doesn't put the heating on in the morning, just 5-11pm. TRVs	£110/month G&E	Income is £600/month. Electric fire is rarely used because of the cost.
E17		Heating on from 7am until 8pm in the winter.	£7,000 year, although in dispute over one bill so could be £6,000	Makes an effort to reduce use. Would like to heat the home more. Had wood burner installed. Very old heating system. New baby, so she keeps the home warm.
E18	N/A	No heating at all.	N/A	No central heating. Gas fire in the living room was condemned and disconnected.
E20		Thermostat. Timer: on at 6.30am-11am, 4pm-11pm. Over-rides timer if wants the heating on at other times. Dial on boiler controls how hot the radiators get. TRV on radiators used to turn down temperature in unused rooms.	£100/month gas, £40/month electric. Prepayment card.	Electric fire in living room which is occasionally switched on during the day as an alternative to central heating, although usually overrides timer.
E21	Heaters set to 21	Temperature dial on electric storage heaters. Heaters also have booster fan which will warm straight away (rather than the storage bit, when temp change wouldn't be implemented until overnight).	£25/week	Economy 7. No gas. Economy 7 means that heaters off at 8.30am summertime, 7.30am wintertime, back on again at 5pm
E22	Thermostat set to 20	Temperature dial on electric storage heaters.	Currently paying £45/month but is about £980/year	Economy 7. No gas.
E23	Thermostat set to 21 but turns it up to 23 when it snows. Hall heater set to 16.	Temperature dial on electric storage heaters.	£125/month	Economy 7. No gas.
E24	Thermostat set to 17-18	Boiler on all the time in winter and has a remote temperature dial. If he feels too warm he switches the boiler off.	£150/quarter gas. £20/month electric on prepayment.	
E25	House very hot.	Turns the boiler on and off as needed. TRVs	£40/month gas. Electric £50/month	Recently had a new boiler which decreased gas by about £25/month.
E29	Thermostat set to 25-30	Thermostat which is used to turn heating on and off as required. TRVs	£150ish/quarter gas and electric.	Gas fire but not used very often. Also had solar panels installed.
E33	Thermostat set to 20	Central heating on for a couple of hours in the morning.	£26/month gas, £46/month electric.	Also has a fan heater he uses if it gets cold during the day or when his Mum's dog is staying.
E34	Thermostat set to 19	Thermostat. Heating on 7.30am- 8pm	£15/month gas, £15/month electric.	Until recently on a Stay Warm tariff which was a flat fee regardless of how much fuel used. Bedroom not used and bedroom radiator off.
E35	Thermostat set to 15	Thermostat. Left at 10 overnight and turned up when he gets up or gets home. TRVs.	£45/month gas £20/month electric	Home feels very warm when thermostat set to 15.

E36		Thermostat. Heating only on in the evening, 8pm – bedtime.	£77/quarter gas. £40/quarter electric.	Doesn’t use the radiator in the bedroom or bathroom to keep costs down.
E39	Thermostat set to 21.	Central heating programmed to come on twice a day.		Uses an electric heater in daughter’s bedroom.
E40	Thermostat set to 19.	Central heating programmed to come on three times a day.	Was £260/month. More recently £45/month for gas and electric In credit so payments lowered to £20/quarter gas.	Recently had new windows and a new boiler. Had been using an electric fire so electric bills had been very high.
E43	N/A	Air source heat pump.	Previous occupants reported heating bills were £400/month	Complete refurbishment. Hoping for passivhaus.
E45	Thermostat set to 18.	Uses the thermostat to turn the heating on and off. TRVs are not used – left at maximum setting.	Gas £100/quarter, electric £106/quarter	Flat is sunny so is usually warm. Has a fan heater that is never used.
E46	Thermostat set to 15.	Uses the thermostat to turn the heating on and off. On when she gets up for about an hour. On again in the evening. TRVs not used – permanently on 3.	£21/month for gas and electric combined, recently reduced from £27 as was in credit.	Keeps the house cold to keep the bills low.

While many participants used a thermostat to control the temperature in their homes, most had old homes and the thermostat temperature was not necessarily accurate. Most paid their bills using direct debit and were able to report their monthly payment, although this did not necessarily reflect consumption as the direct debits could be adjusted up or down depending on whether their account was in credit or debit.

The results show that there is substantial variation in how much participants pay for their energy, even when their homes are the same type, e.g. E1, E2 and E3, and E21, E22 and E23.

It was striking that few of the participants had any understanding of how to use the controls on their boiler to adjust the temperature of their homes. Most had a thermostat in a living area that they used to control the temperature and some had their heating on continually and used the thermostat to turn their heating on and off, as illustrated in the following quote from an interview.

> *"Basically if I'm just going to put it on for an hour I just override it, otherwise it's set on a timer that's all behind there, which I haven't got a clue how to work. I have to get help, you know, to set the timer but like now if I just want to put it on for an hour I'll think oh it's warm enough and then I'll just turn it off, you know what I mean?" E8*

One participant described how they have to turn the central heating on in order to get hot water. They discussed how this isn't a problem in the winter, but the house gets too hot in the summer. They knew that this isn't usual but didn't know what to change on their boiler. Because the boiler had recently been serviced, they assumed it wasn't a boiler fault but nevertheless did not know how they could change things. During the third interview the participant explained that this problem had now been fixed, and had required a simple adjustment to the boiler settings, although she did not know exactly what had been done.

> *"You shouldn't have to put the heating on to get hot water. I mean they've had it serviced only last week, full service, there's nowt wrong with it. So we don't know. It's just maybe how it is. It's weird. It's not an old boiler as well. I've always said it's not right because it's obviously you have your heating and your hot water, it's separate things but maybe they've turned something up there that we don't know about because we don't know a lot about them." E2*

8.4.2 What are people's expectations and experiences of living in a more energy efficient home?

In this section we report a thematic analysis of the interview data using the research question: "What are participants' expectations and experiences of living in a more energy efficient home?". We found three themes in the data: managing the cold, which describes how participants use their heating in order to maintain an acceptable level of comfort; beliefs about retrofit, which describes what participants believed about the insulation, the scheme itself, and what they hope it will achieve; and enjoying the outcomes, which explore the difference that the insulation has made. Figure 8-1shows a thematic map of the data and the themes are described below, supported by quotes from the interviews. The final report will include a more expansive account of the themes and sub-themes.

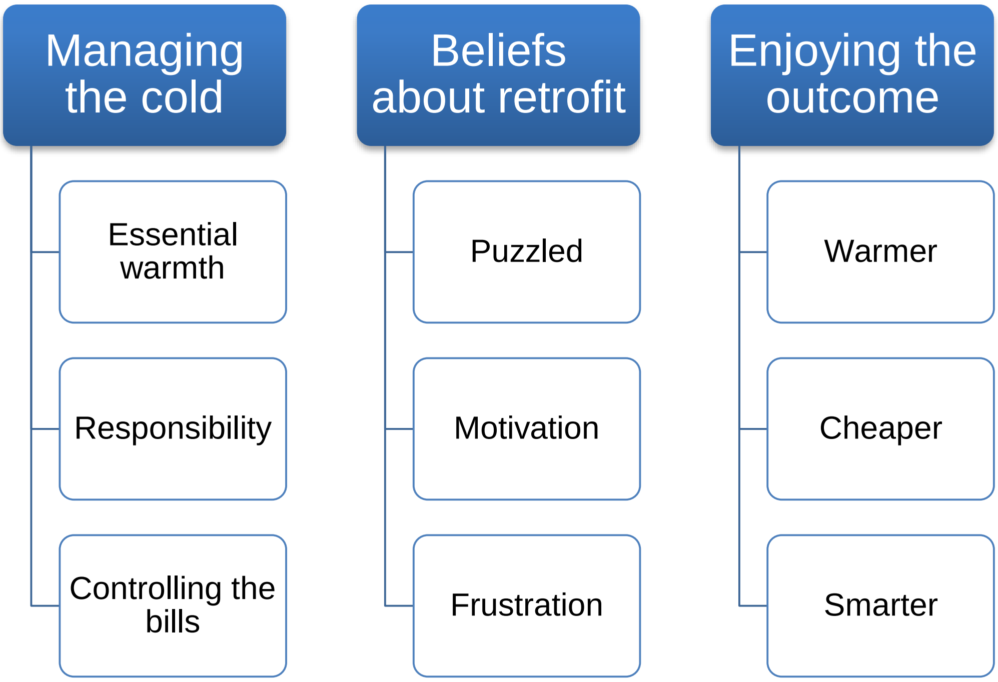

Figure 8-1 Thematic map of people's expectations and experiences of living in a more energy efficient home?

Managing the cold

This theme explores how people try to manage the cold to try to make their homes comfortable, including how they have a need for warmth and comfort, how they feel a responsibility for providing warmth for the people and pets who live in their home, and the steps they take to try to control their energy bills.

Essential warmth

Nearly all the participants wanted to maintain their home at a temperature they consider warm and comfortable. They were not prepared to be cold in their own homes, even though many found it difficult to keep their homes warm. One participant described how she maintains three separate jobs in order to pay her bills, and she would rather work hard than be cold.

> *"My daughter goes, "Your energy bills are twice mine" sort of thing but I don't like the cold, but I find it, especially like even now when it's getting warmer, when it gets to*

> *evening you need to put the heating on for a while because it does…like I said, with them being concrete construction when it's warm they're warm, when it's cold they're like ice boxes and even in summer, as it gets cold on an evening, you do feel the temperature drop quite a lot, you know what I mean, but I'm just soft, I like to be hot." E8*
> *"Well it is a lot [of money to pay for the bills] but I mean, if you want to be warm you've got to use it, haven't you?" E19*

Some people with very inefficient homes were spending substantial amounts of money on energy but sometimes didn't realise how unnecessary this should be.

Despite trying to keep their homes warm and comfortable, people still had cold areas in their homes, sometimes because of air vents, or in rooms with cold external walls. Participants talked about their homes as draughty and cold. Mostly there were some cold areas of their homes, although some participants found their entire home cold, draughty and difficult to heat.

> *"That heat is just basically; it's just flying out those doors. On a night it's freezing because the draught's coming through the door." E2*
>
> *"The little computer room I've got in there, it's very very cold in there." E3*

One participant talked about their home getting so cold that they were unable to use some of the rooms in the winter months because they were too cold or too damp.

> *"Always we play on this side of the house. You know I put bed here sometimes, I put four kids' beds in the sitting room because in their bedroom that very cold, you know. I change. I put this side to play my kids to sit and watch TV and play computer." E7*

Responsibility

People with families talked about how they have no choice but to heat their homes regardless of the cost as they couldn't let their children be cold; they were concerned that cold would make their children ill. Those with pets often talked about how they need to keep their home warm to ensure their pets are comfortable.

> *"I'm struggling but what can I do. You know my kids have to feel warm. If you don't feel warm you feel miserable. If I didn't keep this house warm, the children would be sick, you know, they don't eat well. So I have to really." E7*
>
> *"Because both me and my partner work inside [our home] and also I've got birds that need certain temperatures and I've got pets, that is an issue that unfortunately I just have to… I'm at the mercy of the energy companies and that's it, really." E13*

Participants talked about how they prioritise their heating bill when managing their money. One participant, who has three small children with health problems, talked about how he would pay his energy bills before other bills, such as his rent.

> *"We've even told the council that if we need to pay for heating we'll do that before they get the rent." E25*

Controlling the bills

All the participants were very aware of how their energy costs had increased over recent years, and cost was the primary consideration driving their desire to reduce energy consumption. People talked about how much their energy bills had gone up and in many cases they were struggling to pay them. They were often incredulous about how much it could be to heat a small house for one or two people.

> *"How can it be this much for two people. I don't understand it!" E2*
>
> *"Well everybody I know goes, "How much?" because you know I pay about £110 a month for gas and electric and my daughter says, "I've got a five-bedroom house and you pay double what I pay" you know what I mean? E8*

Many participants were careful about how much energy they used, and a few deliberately kept their homes colder than they would like in order to save money.

> *"If I put the gas on all the time it [the bill] will just rocket so I'm very careful; I can't have it on all the time." E33*
>
> *"Sometimes when it gets cold you think "Shall I put the heating on?" and I think, no, it's only September. I'm not putting the heating on." E11*

Some participants had already tried to improve the energy efficiency of their homes by actions such as installing loft insulation and new windows. Others used more low-tech methods such as hanging blankets over the windows.

> *"Well I think I did everything. We had loft insulated as good as it could be but there's no cavity wall. So I had double glazing put in because there were wooden windows initially. I put the porch on the front to reduce draught coming through there. I put a decent double glazed back door on. So I don't think I could do anymore without, you know. Nothing else I could do to be honest." E17*

Most of the time, however, people had changed their energy tariff as a means of trying to reduce their energy bills rather than making their homes more energy efficient. They had tried various tariffs and had changed suppliers, and viewed this as a relatively easy way to save money. Most were disappointed with the amount they actually saved, though.

> *"Our philosophy is if we're cold put the heating on. We're constantly looking at where we can save money with the gas bills, looking at different companies, but other than that we just use it as we need to." E12*

Beliefs about retrofit

This theme describes how people made their decision about whether or not to have the improvements done, including what attracted them to the scheme, any barriers they anticipated, and the benefits they hoped the insulation would lead to. There are three sub-themes, described below.

Puzzled

Participants were mostly unfamiliar with EWI and had not come across this form of insulation before. They had very little idea of what it would involve. What little they knew about it was based on literature about the scheme delivered to their homes, and from discussions with contractors about the potential benefits.

> *"It's like an overcoat on your house." E1*
>
> *"Well it will keep it warmer, put your bills down. It might cut down on the noise, because this road, like the back of the house isn't so bad but the front of the house, especially when I'm working late on a weekend, on a night, I can't sleep in on a morning because of the traffic. So it may be an advantage, I don't know." E8*

Even after they had agreed to the scheme they did not always understand what the insulation would be or what the installation process would involve. Most of the participants on the council schemes learned more about EWI and what it involves by talking to their neighbours whose homes had already had the improvements done.

> *"I actually thought it were where they drill it into the walls. I didn't know it were going to be the padding until I saw what they were doing over road." E2*

Very few of the participants expressed any concern about potential disadvantages of EWI. They assumed that if the scheme had council and government backing then it must be a good thing.

Motivation

Most of the participants lived in council or social housing and had no choice about which type of energy efficiency measures would be installed, and indeed, whether or not their home was insulation. Only four of the participants would be contributing towards the cost of the retrofit. For them, it was very important that the improvements would pay for themselves. They wanted much more information about the work that would be done, how much it would cost, and how much they could expect to save on their energy bills. Two of these participants had difficulty getting this information. The contractors could provide very little details of how the EWI would be installed, the finish that they could choose from, and for one of the participants, whether a combination of external and internal insulation would be required. One participant had received a Green Deal assessment but was still unclear about the extent of savings, and had been given a very high quote for the work that would be done (in the region of £12,000). They subsequently decided against having EWI installed and instead replaced the windows and installed further loft insulation. One participant decided against EWI when he saw how it was being installed in homes in neighbouring streets: he was concerned that it would lead to damp.

> *"I think it's going to cause a lot of damp issues because it's basically, from what I've seen, polystyrene, I don't know, 50mm thick fastened to the wall with some form of plastic rod. And then they just render over it and do this brick effect. But personally, when water comes down off the roof and what have you it will get damp between the wall and this insulation and it's going to have nowhere to go apart from inwards into the house. And this is the reason I haven't had it done, because I can't see the point of spending £1,000 or so on having it done to cause myself problems in my own house." E20*

Getting a clear quote for the work was very important to participants who were paying for the work, particularly when they had contacted the council about a scheme they had seen advertised. Their decision about having EWI was driven primarily by saving money with the work paying for itself within the time period over they expected to remain living in the house.

Participants whose landlord (either social landlord or the council) was installing insulation as part of a development-wide scheme were less concerned about the outcomes. During the interviews participants talked about what they wanted to achieve from the insulation. Most had relatively low expectations, and hoped that their homes would feel a little bit warmer, and therefore their energy bills would be a little bit cheaper. Nevertheless, they talked about how any reductions in their bills, no matter how small, would be very welcome. They had not based these expectations on any advice or calculations, but rather because their insulation had been free, they did not have any savings that they would need to make to offset its cost.

> *"Well hopefully it'll be cheaper on energy bills, yeah." E1*

Many participants assumed that because the council were responsible for the scheme then EWI must be effective.

> *"It's got to improve it, hasn't it I mean otherwise why would they bother in first place." E2*

Relatively few of the participants kept their homes colder than they would like, so increasing the internal temperature wasn't a priority for most of them. Indeed, most viewed warmer and cheaper as interchangeable as if their homes were warmer their fuel bills would be lower.

> *"Well I don't think it's going to make a lot of difference, is it. Just as long as it's a bit warmer, that's all, yeah. We might be able to turn it [the heating] down a little bit." E1*

It was striking that environmental benefits weren't a priority, or even a consideration. None of the participants spontaneously mentioned environmental considerations, although when prompted, some recognised that there might be benefits. Others had not even heard of such matters.

> *"Well we've never even thought about it but yeah, I suppose. They won't be as many greenhouse gases going outside now, will there?" E1*
>
> *"What's that? I wouldn't know anything about that." E12*

Frustration

Some participants were frustrated that EWI was being imposed upon them and believed there were much more urgent repairs required to make their home more energy efficient. They felt frustrated that they had no choice in the type of improvements that were being carried out. They talked about having poorly fitting doors and windows, and so even if the EWI meant that heat did not leak so much from the walls, their homes would remain cold, draughty and expensive to heat.

> *"The wind just whistles through these windows. There are massive gaps where they don't fit properly. You can be standing on the opposite side of the room and still feel the draught, and that's with the curtains closed. So I don't understand why they don't use the money to replace the windows. It would save far more money." E10*
>
> *"The council would be far better replacing the windows. We've had ours done already, it was the first thing we did when we bought the house. But people who don't own their own homes have still got the original windows and it must be so cold in their homes." E12*

Some participants had been deterred by the potential inconvenience of having workmen in their homes. They were reassured by what they learned about how EWI would be installed, and how it would involve very little mess and would be much less of an inconvenience to residents than would be the case with IWI.

> *"There's less mess with having it on the outside." E1*
>
> *"It's less hassle I think, quicker." E2*

Many of the participants felt frustrated during the installation process as it took a lot longer than they had anticipated. They often complained about poor quality workmanship and about their gardens being damaged or left messy. Some participants believed that the workers took greater care of the private properties on their development.

There were mixed opinions about the quality of the work undertaken, however. Some participants highlighted what they believed to be cost-cutting measures that means that the insulation wouldn't be as attractive as it might be.

> *"I mean I know they won't spend it but they should have done the fascia boards. Tidy them up. Why spend all that money just to leave two little fascia boards on every single one? It just looks…apart from the private ones that have got their own but like I say this one hadn't so it would make them look better for another £40, you know what I mean, like that." E2*
>
> *"Look at that, they've not done a good job at all. It's a right mess. With just a bit more care it could have looked really good, but it's just not straight. I'd have complained if they'd have left my house looking like that." E8*

Enjoying the outcomes

This theme describes the benefits that participants experienced from their insulation, namely it being warmer, the bills being cheaper, and their local environment being smarter and more pleasant. The three sub-themes are described below.

Warmer

Nearly all the participants talked about how their homes were noticeably warmer since the insulation had been installed. Some described the difference as being slight and others that it had made an immediate and noticeable difference to how warm their homes were.

> *"It's absolutely fantastic. I can't believe what a difference it's made. It's remarkable, it really is. You could tell immediately. We came downstairs and thought – this is so much warmer. I didn't think it would make that much difference." E22*
>
> *"In general the whole flat is warmer. When I get up in the morning it can be white all over with frost outside and I don't have to put the heating on." E45*

Some participants identified that the insulation had made their homes more airtight by blocking the draughts that had made their homes feel so cold.

> *"I've got to say the differences I've felt so far, because there were two vents in the kitchen where the sinks are and basically they've covered them up and the draught's just gone. So I'm glad about that because it was cold in winter. It's a big, massive difference. If it were cold out there and windy you could feel the wind coming through the cupboards. And the porch, we can't really tell at the minute. It's still cold but not as cold." E2*

Participants talked about how their homes now retain heat much better than before the insulation. When they return home they now notice that their home is much warmer than it used to be and it heats up again much quicker.

> *"When I get home I just put the heating on and within sort of 20 minutes, half an hour everything is warm. I don't feel like I'm coming into an icy cold house any more so you can feel the difference – it's not Brrrr!" E8*

A few participants talked about how they had not noticed any difference at all to the temperature in their homes. However, both these participants deliberately keep their homes at a lower temperature than they would like to keep the bills low. E46, in particular, heats her home rarely and did not appreciate that the EWI needs heat to keep within the home.

> *"I can't tell any difference, it's still really cold in here, well I am really cold, and my bedroom's absolutely freezing." E36*
>
> *"It's made no difference at all. I'm really disappointed, I thought it would feel warmer but it doesn't. Well upstairs, maybe it's ever so slightly warmer, I'm not sure. But downstairs, no." E46*

Some of the participants had damp walls in their homes and they had noticed that this had improved substantially, or in some cases, the walls had dried completely.

The participant who could not keep her home warm talked about an advantage of EWI being that the house would be warmer and so her family could use the whole house in winter months rather than staying in the warmer rooms. Another had now started using her bedroom as it was warm enough to sleep in. This meant that she could sleep in a proper bed and not on the settee in her living room.

> *"The kids can play wherever they want, you know. Before they stick in here [the living room]. All the times they play here because I don't want them feel you know cold because here is warm. Now they can be free, all the house, yeah? They can play everywhere, wherever they like." E7*

Some participants described how living in a warmer home meant that they felt happier or more optimistic.

> *"When you're a lot warmer you feel more cosy and relaxed, because I do suffer with my nerves and depression and all that. Don't seem to be so bad with it now. It's good, I look forward to coming home on an evening if I've been out walking and get it all warm in here and it's relaxing. It's a comfort thing. It feels peaceful." E33*

Cheaper

Many participants talked about saving money on their energy bills since their home had been insulated. For most, this was the most important benefit they hoped to achieve. Many had noticed that their bills had reduced or they had received a rebate from their energy provider.

> *"We're saving a fair bit, we're only spending £20, £25 a month on gas and most of that is cooking. We used to spend, before we had the cladding done, £50 for the month." E25*
>
> *"I've done really well because I'm waiting to get a rebate back. I was using less gas all last year and now I'm £800 in credit. I thought I might be using more because I'm now heating my bedroom. I'm waiting for the cheque and I'm going to get a new carpet in here." E34*

Others, however, were less clear whether they were saving money. Because most pay a fixed amount on direct debit, they aren't aware whether or not their consumption had changed. When their energy providers had lowered their direct debit they realised they were using less gas, but often they were unaware. The direct debit payment scheme has introduced a disconnect between energy use and cost.

Smarter

An additional benefit was that people believed the appearance of their local area had improved. They had seen other houses in their area receiving EWI and very much appreciated the way the houses looked.

> *"They look nicer. They look like they're new again, you know what I mean." E1*
>
> *"It just makes the area look nicer, makes it look cleaner. A lot of people say the area looks nice, it just cleans it up because before it used to be just stones and it used to look dated. It just looks brighter and it makes my partner feel a bit better, it cheers her up because it looks nicer." E25*

After the improvements had been made, participants were very positive about their area appearing more attractive. Despite a few participants highlighting problems, most were very happy with the work that had been done, and were happy with how the contractors had cleared up the area after the work had been completed.

Several participants had or were planning to redecorate their homes: they talked about how they wanted their home to look nicer now it is warmer. One had not been able to redecorate previously as some of the walls in his home were too damp, but since the insulation the walls had dried out and could now be decorated. Many felt much more proud of their homes since the insulation had been installed.

8.4.3 Has the insulation met participants' expectations?

In this section we report the results of the survey on comfort with the home's temperature and any effects on health, and the results from the interviews on expectations of the benefits that participants hoped to gain from their insulation.

During each visit participants completed a comfort-taking questionnaire, adapted from that used in the Salford research group. The questionnaire includes items about how comfortable the temperature within the home is, how much control people have over the temperature, and how often the home is too warm or too cold. The percentage giving each response is shown in the following tables.

Table 8-3 Perceptions of temperature and air quality at T1, T2 and T3

		Very Poor	Poor	Average	Good	Very Good
How comfortable is the temperature in your home?	T1	3%	13%	29%	47%	6%
	T2	0	0	9%	55%	36%
	T3	0	0	0	42%	58%
How good is the air quality in your home?	T1	0	13%	32%	45%	10%
	T2	0	0	27%	64%	9%
	T3	0	0	33%	58%	9%

The mean thermal comfort rating increased from 3.42 at T1, to 4.27 at T2 and to 4.58 at T3. A repeated measures ANOVA showed that the increase in comfort rating between T1 and T2 and between T1 and T3 is significant, F (2,22) = 8.97, p = 0.001.

The air quality rating increased from 3.52 at T1 to 3.82 at T2 and fell again to 3.75 at T3, although the increase was not statistically significant.

Comfort ratings are shown alongside monitored temperature data in Table 8.4. This shows that there is at times poor alignment between self-rated and objective thermal comfort. Some of these discrepancies can be explained from the qualitative data. For example, neither occupant in E3 was home during the day and while they talked about their home being cold on their return from work, they are happy with how quickly it heats up in the evening. The temperature in E11 was very cold but the occupant talked about how she has low expectations of warmth, as all the homes she has lived in have been cold. Likewise, E18 was very cold but the occupant had made a decision not to install any heating at all, and so his rating was affective by "cognitive dissonance", in which he found it difficult to reconcile having an uncomfortably cold home with deciding not to install heating. E34 lived in just one room in her home and did not occupy the bedroom and was happy with the temperature in this one room but found the rest of the home cold. E35 and E37 had both recently had central heating installed and so the occupants were enjoying much more comfortable temperatures, even though the temperature indicates that his home was uncomfortably cold. These examples illustrate the importance of including a qualitative element alongside an occupant survey in retrofit evaluations.

Table 8-4 Thermal comfort of dwellings

Dwelling	Objective rating before retrofit	Subjective rating before retrofit	Objective rating after retrofit	Subjective rating after retrofit	Monitored temperature increased after retrofit?
E-1	3	Good	3	Good	No
E-2	3	Average	3	Good	No
E-3	Uncomfortable	Good	3	Very good	Yes
E-7	-	Good	2 & 3	Very good	-
E-8	3	Good	3	Good	No
E-9	3	Good	3	-	No
E-10	3	Poor	-	-	-
E-11	Uncomfortable	Average	-	-	-
E-12	3	Good	-	-	-
E-13	3	Good	-	-	-
E-14	3	Average	-	-	-
E-15	3	Average	3	Average	No
E-16	2	Good	2	Average	No
E-17	3	Poor	3	-	Yes
E-18	Uncomfortable	Very good	Uncomfortable	-	No
E-20	3	Average	-	-	-
E-21	3	Good	3	Very good	No
E-22	3	Average	3	Good	Yes
E-23	3	Very good	3	Very good	No
E-25	3	Average	3	Very good	No
E-29	3	Good	3	Very good	No
E-33	3	-	3	-	No
E-34	Uncomfortable	Average	3	Good	Yes
E-35	Uncomfortable	Average	3	Good	Yes
E-36	3	Good	1	Good	Yes
E-37	Uncomfortable	Good	3	Good	Yes
E-39	3	Poor	3	Good	Yes
E-40	Uncomfortable	Very poor	-	Good	-
E-45	-	Good	-	Very good	-
E-46	-	Good	3	Good	-

Most participants reported having good control over their thermal comfort (Table 8-4). Ratings of control over comfort increased from 3.74 at T1 to 3.95 at T2 and 4.08 at T3 but this increase was not statistically significant.

Table 8-5 Perceptions of control over temperature at T1, T2 and T3

		No control	Little control	Average control	Good control	Very good control
How good is the control over the temperature in your home?	T1	3%	3%	32%	39%	23%
	T2	0	5%	18%	55%	23%
	T3	0	8%	0	67%	25%

Table 8-6 Perceptions of extreme temperature at T1, T2 and T3

		Never	Occasionally	Sometimes	Often	Always
Is your home ever too warm?	T1	32%	29%	39%	0	0
	T2	32%	32%	36%	0	0
	T3	25%	25%	42%	8%	0
Is your home ever too cool?	T1	13%	13%	32%	36%	7%
	T2	54%	14%	32%	0	0
	T3	50%	33%	17%	0	0

The questionnaire included the single-item Euroqual health measure, in which participants are asked to rate their health today on a scale from 0 to 100, with 0 being the worst health they could imagine and 100 being the best. The mean score was 70 at T1 and there were no significant changes between T1, T2 and T3.

To identify whether participants' expectations of the benefits of insulation have been met, data from the interviews were extracted and are summarised in Table 8-7.

Table 8-7 Whether participants' expectations of their insulation have been met

	Aims	Outcomes	Comments
E00	Warmer	Achieved.	Home feels warmer. Heat is retained for longer.
E01	Warmer	Achieved. Thermostat set to 20 (was 19)	Bills lower, now £60 gas and electric/month.
E02	Cheaper (at T2 said warmer)	Feels a little bit warmer. No change in the bills.	Also makes the area look much nicer.
E03	Cheaper	Achieved. Bills decreased from £140/month to £100/month.	Heating on for less time as heat is retained longer. Thermostat still set to 21. Couple have retired and are now in the home all day but nevertheless using less gas. Fewer draughts now.
E07	Cheaper	Achieved. Bills reduced to £71/quarter. Also much warmer.	Very happy with the insulation. Also makes the area look much nicer.
E08	Cheaper	Achieved. Gas and electric bill reduced from £110/month to £95/month.	Home feels warmer. Heat is retained for longer.
E09	Warmer and cheaper	?	Follow-up interviews not completed.
E10	Warmer	N/A	N/A: insulation not installed

	Aims	Outcomes	Comments
E11	Warmer	N/A	N/A: insulation not installed
E12	Cheaper	N/A	N/A: insulation not installed
E13	Cheaper	N/A	N/A: insulation not installed
E14	Warmer	?	Family moved.
E15	Cheaper	No	Not noticed any difference at T2. Family moved before T3.
E16	Cheaper	Achieved	Heat is retained for longer.
E17	Cheaper	Achieved, although EWI not installed	Substantial reduction in energy bills: from £6000 a year to £2,000
E18	Warmer	?	Follow-up interviews not completed.
E20	Warmer	N/A	N/A: insulation not installed
E21	Cheaper	Achieved	Energy bills reduced from £120/month to £60/month. Temperature on heaters reduced from 21 to 19/18 and two heaters (spare bedroom and bathroom) turned off. The house is now less damp.
E22	Cheaper	Achieved	The bills are lower and the house is now warmer and heats up faster. The electric heaters are set to a lower temperature (19-20). The house is now less damp.
E23	Cheaper	Not sure about whether the bills are lower because in dispute with energy provider.	The house is warmer but it is now damp. The housing association requested to install loft insulation but participant refused.
E24	Warmer	Achieved	Home now much warmer. Thermostat set to 23. The windows were painted closed when the work was done, and the ventilation bricks covered over which means that the home can overheat.
E25	Cheaper	Achieved. Gas bills reduced from £40-50/month to £20/month	The home is warmer and heat is retained for longer. Heating used to be on all day and is now on a timer. On for 45 minutes in the morning and off until the children are home from school.
E29	Less damp	Achieved	Less damp, less mould and the home retains warmth better
E33	Warmer	Achieved	Still careful about how much gas is used but the home is warmer, heat is retained for longer and the home is less damp. Now in credit with the energy provider, suggesting using less energy.
E34	Warmer	Achieved	In credit with the energy provider, which suggests bills are lower. Feels a little bit warmer and now using the bedroom that was previously too cold (and couldn't afford to pay for a carpet for it).
E35	Cheaper	Achieved	Has the heating on for shorter periods of time and the gas bill is lower.
E36	Cheaper (and warmer)	Hasn't noticed any change	Most important is cheaper but also very important that it is warmer – will keep it warmer if the bills are lower. Reported that there had been no change, although now putting the heating on more during the day.
E39	Warmer	Achieved.	Thermostat now set to 17 (was 21) and no longer need to use the additional electric heater. Home retains the heat for longer.
E40	Cheaper	?: no T3	
E43	N/A: family refurbishing a house before moving into it. Important that it is highly energy efficient. Motivated by being environmentally friendly and low energy bills.	?: no T3	
E45	Cheaper	Achieved.	Gas bill reduced from £100/quarter to £59/quarter
E46	Warmer	No	Reported that it is possibly a bit warmer upstairs but no obvious change.

9 Discussion

9.1 Contextualising the results

This section attempts to summarise the findings for individual homes to identify if there are any mitigating factors that need accounting for or if there are any trends specific to dwelling characteristics that can be identified.

9.1.1 Retrofit performance

Table 9-1 summarises the results from the eighteen dwellings which passed the quality control data analysis procedures. It lists their improvement in energy efficiency according to each analysis method:

- energy use per Heating Degree Days (kWh/HDD);
- power temperature gradient (PTG);
- energy use per Dwelling Heating Demand (kWh/DHD); and
- Dwelling Heating Gradient

All eighteen dwellings have solid walls; twelve are concrete, five are brick and only one is stone. Table 9-1 suggests the average improvement achieved in each of the concrete and brick wall types. As can be seen there is a relatively consistent level of achievement in both types of dwelling, except in the case of the HDD calculations for the solid walled dwellings, however this may be because the sample sizes are small (n=5) and so an unusual consumption pattern in one or two dwellings disproportionally affects mean of the sample.

Table 9-1 Average retrofit improvement in energy efficiency (negative value indicates increase in energy after retrofit)

Wall type	kWh / HDD (> 150 HDD)	PTG (> 0.4 R^2)	HDG (> 0.4 R^2)	kWh / DHD (> 150 DHD)
Concrete (n=12)	14%	27%	27%	28%
Brick (n=5)	-1%	32%	33%	34%
All dwellings (n=18)	4%	28%	29%	20%

Table 9-2 presents more in depth data from comparing the performance of each individual dwelling and is the data used to produce Figure 7-17 which also identifies what retrofit was undertaken. EWI is the predominant measure undertaken and few if any secondary measures were undertaken. Although this means no comparison can be draw between retrofit types, it does mean the findings of the monitoring part of this project could, with some confidence, be extended to other EWI retrofits.

Table 9-2 Retrofit improvement per dwelling (negative value indicates increase in energy consumption after retrofit)

Dwelling ID	kWh / HDD (> 150 HDD)	PTG (> 0.4 R^2)	HDG (> 0.4 R^2)	kWh / DHD (> 150 DHD)	Measure 1	Measure 2
E-01	30%			35%	EWI	LI
E-02	44%	59%		55%	EWI	
E-03	29%	44%	50%	46%	EWI	
E-09	6%	-12%	12%	8%	EWI	
E-15	-63%	5%	16%	-73%	EWI	
E-17	-86%			-137%	LI	Windows
E-21	27%	31%	17%	23%	EWI	
E-23	-105%	18%	26%	18%	EWI	
E-25	13%	43%	37%	46%	EWI	
E-30	26%	46%	38%	33%	EWI	
E-32	19%			8%	EWI	
E-33	-10%		-43%	10%	EWI	
E-34	47%	52%	60%	65%	EWI	
E-35	22%	50%	62%	58%	EWI	
E-36	3%	-23%	6%	36%	EWI	
E-37	26%		40%	43%	EWI	
E-39	32%		52%	50%	EWI	
E-41	15%			44%	EWI	

It is interesting that the results from the HDD analysis method are the least similar to those from the other methods. This may be because HDD makes assumptions about the internal temperatures in each dwelling that may not be realistic. This may also be why the HDD analysis suggests the most modest retrofit improvement in this project. Figure 9-1 shows the HDD set point assumption of 18°C relative to the daily average internal temperature for the dwellings, which vary between 12°C and 24°C. The before daily average internal temperatures below 12°C were recorded in unoccupied dwellings undergoing a retrofit. This variation in internal set points has a significant bearing on the apparent energy efficiency of a dwelling and therefore the appropriateness of using HDD analysis. This suggests that HDD set point may be underestimated for our sample, though it is not known if this is the case on a national scale since this is based on a small number of dwellings.

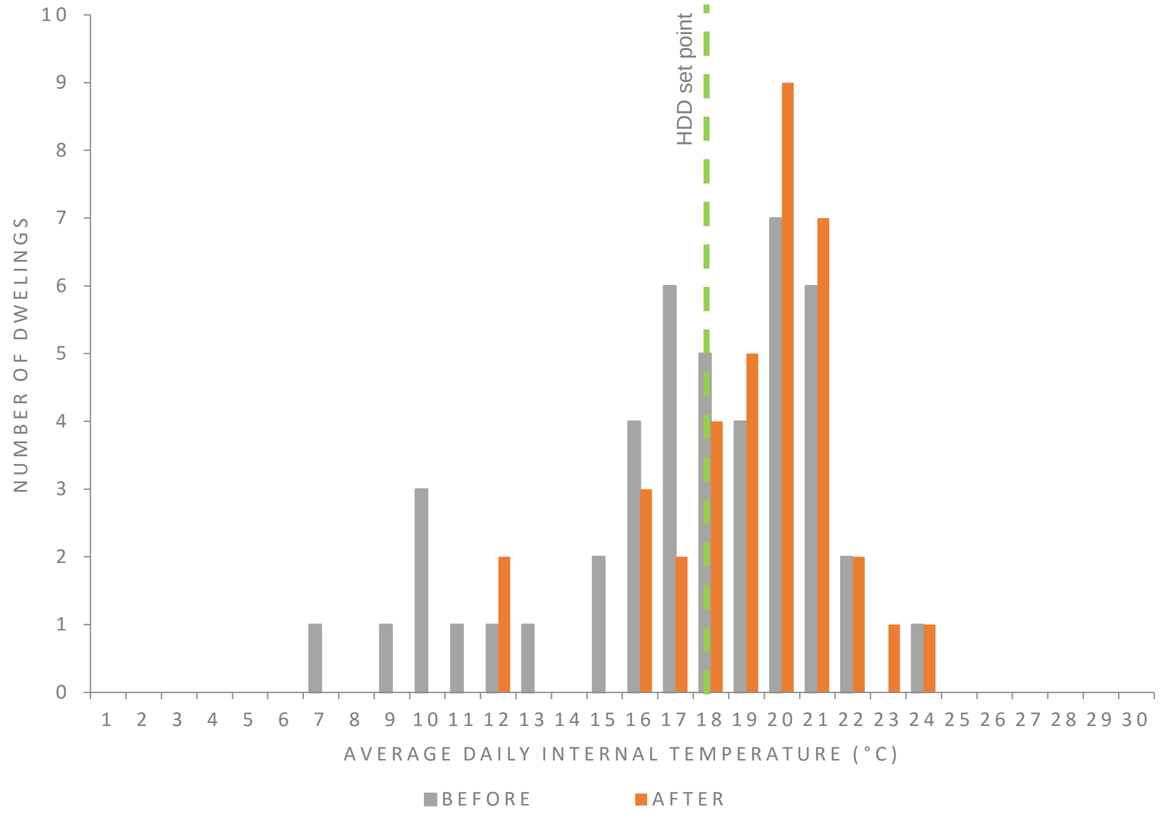

Figure 9-1 Internal daily average temperatures observed in dwellings

9.1.2 Linking monitoring results to other data

It is possible to contextualise the results of the project further by investigating the survey and interview data, and the thermal comfort analysis alongside the monitoring results. For example, it was known that during the monitoring period in the stone property E-17; a baby was born, a log burner was installed and building work took place, all of which may have compromised the data. Additionally, it has an extremely low before gas consumption indicating that perhaps some amount of secondary heating was being used. However, it is also interesting to note that this is one of only four dwellings that experienced an increase in energy consumption and it was the only one that did not have any solid wall insulation fitted due to funding scheme changes and the cost of additional remedial work.

The three other houses that experienced an increase in energy consumption after the retrofit, also each had a very low energy consumption to begin with (<0.06 kWh / DHD / m^2) making any changes in energy consumption difficult to characterise. In addition, two of these were actually only shown to have increased their energy consumption according to the HDD assessment method, so this may be a conservative assessment of the retrofit improvement.

Analysis of the adaptive comfort plots for these three dwellings where increased energy consumption may have taken place, indicates that there has been no obvious comfort taking that could have explained the trend. No air tightness measurements for these dwellings were made, which might have highlighted if there had been poor quality workmanship when relocating penetrations. Subtler causes for the increase in energy consumption must therefore be responsible, highlighting the limitation of using in-use monitoring to diagnose dwelling energy performance trends.

The survey and interview data can provide some insights; for example; dwelling E-33, thermal bridges were observed at the eaves, the loft insulation was poorly installed. This is a first floor flat (so may have complex thermal bypasses and thermal interactions with neighbours). Furthermore, it was situated over an external store that was neither insulated nor draught proofed. In addition, the occupant had been using significant amounts of secondary heating before the retrofit in order to provide a comfortable environment for a dog that they were temporarily looking after. The dog went back to its owner in the *after* period, and presumably the secondary heating was, therefore, no longer used and so the primary heating was required to deliver proportionally more of the heat thus affecting the apparent success of the retrofit. This further highlights the complexity of in-use monitoring projects and the importance of collecting contextual survey and interview data alongside energy and environmental data.

This project has also discovered that savings can be achieved in dwellings even when the retrofits are imperfect. Twelve instances of thermal bridging were recorded for the retrofits in Table 9-2 yet substantial savings were still observed. This suggests that the ability of EWI to reduce fuel bills may be relatively robust. However, no EPC's were provided for the dwellings, so the reduction in performance due to the imperfections (the performance gap) could not be estimated.

Problems effecting condensation (lack of trickle vents, blocked air bricks and existing moisture problems) were found in seven of the properties where energy savings were calculated. It is therefore important to understand that a retrofit may be considered a success in terms of reducing bills, but that unintended consequences may still occur. It was not possible to assess the trade-off between energy savings and unintended consequences since the latter often only manifest after several years. The trade-off between areas that achieve a reduced risk of condensation and those where an increased risk is experienced requires further investigation. It is possible that a whole system approaches might mitigate and control condensation, however very few of the retrofits took this approach. The change in internal environmental conditions and the in-use impact on condensation risks requires further work, as some of the occupants perceived a reduction in condensation and mould.

9.2 Research Objectives

9.2.1 Quantify retrofit success

This project has identified that savings from solid wall insulation (SWI) and particularly external wall insulation (EWI) in solid concrete and brick dwellings can be of the order of 4% to 29% depending on the analysis method used. Within this range there is a great deal of variation on an individual property level and owing to the multiple influences on energy consumption in homes, it is unlikely that any single installation will be able to correctly identify the level of savings that may be achieved for a particular dwelling, indeed, the level of savings will vary from year to year and according to how the dwelling is used.

Nevertheless, these savings are still of the order of or somewhat higher than those observed in NEED. This supports the view that EWI can substantially reduce the heat loss and also therefore dwelling fuel bills. Collecting data on the installation costs was outside the scope of this project and so payback calculations could not be undertaken.

Standard HDD calculations underestimated the likely target set points in the dwellings and so may have under estimated the level of savings that can be achieved. Using PTG, DHD or DHG may provide more robust analyses and these produced more consistent aggregate savings for the sample of between 20% and 29%, although for individual dwellings the predicted savings between each method could vary substantially.

It was not possible to identify the savings achieved by dwellings where IWI was installed through the in use monitoring results. However, the co-heating test results suggested that whole house heat loss can be reduced by between 25% and 56%. Similarly the party wall cavity fill reduced heat loss by 8% and in general the improvements made were largely (70% to 80%) related to fabric improvements, with the remainder being due to improved air tightness.

The project showed that the improvement in dwelling airtightness could be up to 62% where the air barrier is carefully designed. Where this was not the case it was found that incidental improvements in air tightness were on average around 25%, though often this was due to the accidental blocking up of ventilation pathways such as air bricks. The consequent condensation risk following the reduction in air tightness of the dwellings was not assessed though the reduced air tightness is likely to contribute to the energy savings observed.

An important measure of success of a retrofit is the reaction of occupants to the changes and these were generally positive. Major concerns remain around the occupants' understanding of heating controls, and although occupants displayed unexpected energy behaviours which made quantifying the actual improvements in energy efficiency achieved difficult, the majority considered their homes to be more comfortable and affordable to run after the interventions. They also considered that the aesthetic appearance was greatly improved.

9.2.2 Identify underlying causes for the performance gap

The project has made a number of important observations on installation quality and occupant behaviour that are likely to lead to an underperformance of the insulation. These include:

- Gaps in insulation (e.g. around wall mounted objects);
- Penetrations and fittings not being adequately sealed;
- Thermal bridging at element interfaces;
- Installing single measures (e.g. not whole house approach and miss economies of scale);
- Ventilation pathways blocked up;
- Missing insulation around jambs, sills and lintels; and
- Lack of access to install insulation (no IWI behind kitchens, EWI stopping before party wall etc.).
- Complex occupant behaviour
- Changes in household composition

The majority of the retrofits did not require before and after EPC's to access funding and so it was not possible to compare the predicted with the observed savings. However, the co-heating tests have been able to quantify the performance gap for the fabric improvements in two dwellings as 7% and 21% for IWI. The performance gap for the whole house heat loss coefficient (HLC) could not be calculated since the contractors' predictions were only made for fabric elements.

The co-heating tests also revealed significant variation in achievement of a retrofit even for similar archetypes and retrofit measures being installed; C-01 reduced its HLC by 56% while C-02 achieved a reduction of just 25%. This suggests a significant opportunity cost of failing to put resources into the design and implementation of the retrofit. Specifically, it was observed that a well implemented air tightness strategy was able to reduce the overall dwelling HLC in C-01 by almost as much as the fabric improvement achieved in C-02.

Incorporating additional information can help understand situations where either a reduction in energy consumption was smaller than anticipated or indeed where energy consumption appears to increase after a retrofit. One of the major uncertainties facing any analysis of energy data before and after a retrofit is that it is not practical to measure every variable influencing energy consumption.

Weather and internal temperatures can to some extent be accounted for via the methods proposed in this research, however it is more difficult to systematically incorporate data collected on the building condition and interaction with neighbouring buildings, the occupants' heating consumption behaviour and other occupant related influences (internal gains, window opening behaviour, changes in household composition etc.). Therefore, there will always be an element of uncertainty surrounding retrofit evaluation and building performance evaluation in general. While it is not possible to quantify and 'average influence' of these issues it is possible to identify the scale of the influence they can have on the interpretation of the results. In this project we have identified that they can in some instances be relatively minor where data are relatively consistent however in other dwellings they may compromise the findings. Identifying where this is the case is not a simple task but is essential for projects with small sample sizes.

9.3 Policy implications and other observations

This research has identified many issues that may be considered when developing future domestic energy efficiency policy in the UK some of which are discussed in the main report and others which were captured informally through discussions with stakeholders. A summary of these is presented here:

Research observations

- The quality control of installers is inconsistent and generally not robust;
- Around half of the dwellings had some level of damp;
- The air tightness of some homes was very poor;
- For accurate financial retrofit payback predictions, air tightness tests are needed;
- The benefit of air tightness improvements as a measure may be undervalued;
- Party wall cavity fill provides an opportunity for wide scale retrofit;
- Dwellings with similar archetypes and retrofits can have very different outcomes (e.g. 100% difference in heat loss coefficient reductions);
- Installers' approaches are fundamental to the savings that will be realised;
- Current process quality control methods do not guarantee quality installations
- Using average retrofit performance can mask variability in dwelling energy behaviour which mean that dwelling level predictions of energy savings are not realistic;
- Unintended consequences may not manifest for several years and can occur even in homes where energy savings have been observed;
- Retrofits have reduced energy consumption even in imperfect installations;
- Around one third of homes were considered to be under-heated; and
- Comfort taking was apparently taking place in around one fifth of homes.

Observations on research method

- The method of data analysis influences the apparent success of retrofits;
- In-use monitoring projects can provide large quantities of data but often problems limit the amount that may be useful;

- Contextualising energy and environmental data is essential to interpreting the success of retrofits; and
- Variations in dwelling energy behaviour mean that field trials are sensitive to sample size.

General observations

- Funding uncertainty has limited the number of homes undergoing retrofits;
- RSLs have significant uncertainty on the most appropriate retrofits for their stock;
- EPCs are generally not undertaken unless required for funding;
- Very few private home owners are using existing government efficiency schemes;
- Retrofit funding encourages 'just in time' installers which are unsuited to participation in research and monitoring;
- RSLs were very enthusiastic to take part in the research;
- Installers were generally interested to take part in the research;
- Occupants were generally not enthusiastic to take part in the research with some exceptions; and
- Occupants were happy with the retrofits in general, especially as it improved the appearance of their dwellings and often the streetscape.

9.4 Discussion Summary

This project has been a very large undertaking and a huge amount of data was collected on a large number of dwelling retrofits. It has provided some useful and important insights into the success of retrofits currently being installed under government funding schemes. The dataset generated is among the largest and most comprehensive of its kind in the UK and may be further investigated as part of future data mining projects acting as a source of information that can continue to provide insights on domestic retrofits.

The body of evidence collected suggests that retrofits are successful in the most part at reducing energy bills for consumers. One of the greatest challenges that the project has revealed, which is likely to affect domestic energy efficiency policy, is that of accounting for large variations in heating behaviours. This makes it very difficult to provide dwelling level predictions or guarantees of performance.

Evidence suggests that policy may be undervaluing the potential of additional low cost measures including party wall cavity fill and air tightness improvements. However, it has also confirmed that fuel bills can be reduced by retrofit programs and that generally they can improve occupants' quality of life.

10 List of Appendices

A. Dwelling survey pro-forma
B. Air tightness test reports
C. Design review C-01
D. Co heating report C-01
E. Co heating report C-02
F. Co heating report C-03
G. Thermal bridging calculations
H. Hygrothermal simulation data
I. Retrofit performance summary sheets
J. T1 Interview guide
K. T2 Interview guide
L. T3 Interview guide
M. Comfort taking questionnaire