**Cardiff Metropolitan University**

**Ph. D Research Degree**

# Evaluating Retrofitted External Wall Insulation

**Volume 1**

**Joanne Louise Atkinson BSc (Hons)**

Dr J. R. Littlewood (Director of Studies) | Professor A. J. Geens (Supervisor) | Professor G. Karani (Supervisor)

**January 2015**

Thesis submitted in partial fulfilment of the requirements of Cardiff Metropolitan University for the Degree of Doctor of Philosophy

In collaboration with Coastal Housing Group

# Abstract

## EVALUATING RETROFITTED EXTERNAL WALL INSULATION

By Jo Atkinson

The aim of this doctoral research project is to investigate the link between the construction quality of retrofitted external wall insulation (EWI) and the resulting impact on energy performance of existing dwellings in Swansea. Four contributions to knowledge are documented. The first is a methodology for simultaneously obtaining empirical data about the construction quality and energy performance of dwellings receiving retrofitted EWI. The findings demonstrate the value of assessing the construction quality of retrofitted EWI alongside energy performance. The appraisal of energy performance alone could have indicated misleading results due to the omission to identify latent factors, such as thermal bridging, which were identified whilst assessing the construction quality of the retrofitted EWI. The second contribution is a methodology for assessing the construction quality of retrofitted EWI, which can be used as part of the quality control process for future installations. Through the collection and analysis of triangulated field observations of photographs, as-built technical details and qualitative external thermographic surveys, the findings indicate that this methodology provides robust results for assessing the design and execution of retrofitted EWI.

The third contribution is baseline energy performance data for traditional dwellings in south west Wales. The data documenting these results are set out for each case study dwelling, which includes energy consumption and carbon emissions, together with the dwelling type, tenure and number of occupants. The fourth and final contribution is a EWI retrofit case study of traditional dwellings in south west Wales. This is the culmination of the entire doctoral research project, which as a whole does not currently exist in the literature. Collectively, all the individual case studies make up the overall case study documenting the construction quality and energy performance of traditional dwellings in Swansea, which have received retrofitted EWI through phase one of the Welsh Government's Arbed scheme.

# DEDICATION

***To my Nan & Grandad, Joan and Reg,***

***for their belief in me.***

## Acknowledgments

First and foremost my endless gratitude goes to my husband, Simon. If it were not for his continuous support and encouragement; I would not be where I am today and most certainly would not be writing this statement. Simon is always there for me, especially when I need a shoulder to cry on and in need of some stern motivation. Equally my thanks go to my two daughters, Emily and Lily for putting up with having at best a part-time Mum. Their smiles and unconditional love inspires me to keep going. After all this has been about more than just me achieving my potential; this is about me increasing the prosperity for my family. Next I must thank the rest of my family and friends: Grandad (Reg); Nan (Joan); Mum (Nicky); Dad (Dave); Toni; Steve; Anne; and Beck. Over the years they have provided relentless moral and physical support, in particular with looking after the girls so that I can meet my goals and deliver work on time.

Next I would like to extenuate my gratitude to my Director of Studies, Dr John Littlewood who often has more faith in me than I of myself. He has always pushed me to succeed and fulfil my potential and I will be eternally grateful for his inspiration and enthusiasm. I have also received continuous support and encouragement from my other two academic supervisors, Professor Andrew Geens and Professor George Karani, my academic advisor John Counsell, and from Coastal Housing Group my industrial advisor Andrew Thomas and Gary Morgan. In addition, I would like to thank my fellow doctoral scholar, Dr Tim Taylor for leading the way through the different stages and always providing me with the insight I needed to get me through.

Finally I would like to thank my extremely supportive managers and colleagues from my two employers since writing this thesis. First, Rhiannon Perkins from Groundwork whose continuous support allowed me to juggle the hardest writing days with full-time employment, as well as family life. Next, Richard Rugg, Tim Pryce and Jamie Plotnek from the Carbon Trust, my current employer, who have quickly come to share my vision for ensuring that the future of retrofitted EWI is executed to maximise the benefits for everyone. Their belief in me is second to none and as a result I am already realising the fruition of all my hard work.

## Glossary of terms / Abbreviations

| | |
|---|---|
| **AECB** | **Association of Energy Conscious Builders** |
| **BERR** | **Department for Business, Enterprise and Regulatory Reform** |
| **BRE** | **Building Research Establishment** |
| **$CO_2$** | **Carbon Dioxide** |
| **CMU** | **Cardiff Metropolitan University** |
| **CIAT** | **Chartered Institute of Architectural Technologists** |
| **CIBSE** | **Chartered Institution of Building Services Engineers** |
| **CHG** | **Coastal Housing Group** |
| **DCLG** | **Department for Communities and Local Government** |
| **DECC** | **Department of Energy and Climate Change** |
| **DTI** | **Department for Trade and Industry** |
| **ECO** | **Energy Company Obligation** |
| **EPC** | **Energy Performance Certificate** |
| **EST** | **Energy Savings Trust** |
| **EWI** | **External Wall Insulation** |
| **FHA** | **Family Housing Association** |
| **HHSRS** | **Housing Health and Safety Rating System** |
| **IPCC** | **Intergovernmental Panel on Climate Change** |
| **IWI** | **Internal Wall Insulation** |
| **KESS** | **Knowledge Economy Skills Scholarship** |
| **LSOA** | **Lower Super Output Area** |
| **NAO** | **National Audit Office** |
| **NHBC** | **National House Building Council** |
| **rdSAP** | **Reduced Data Standard Assessment Procedure** |
| **RSL** | **Registered Social Landlord** |
| **SPAB** | **Society for the Protection of Ancient Buildings** |

| | |
|---|---|
| **SAP** | **Standard Assessment Procedure** |
| **STBA** | **Sustainable Traditional Buildings Alliance** |
| **TSB** | **Technology Strategy Board** |
| **UK** | **United Kingdom** |
| **UWIC** | **University of Wales Institute Cardiff** |
| **WHQS** | **Welsh Housing Quality Standard** |
| **WIMD** | **Welsh Index of Multiple Deprivation** |

## Table of Contents

## List of Figures

## List of Tables

# Chapter 1: Introduction

# Chapter 1: Introduction

This chapter introduces the reader to the research project, which has the primary focus of producing a case study from data that has been collected by the author to assess the effectiveness of retrofitted external wall insulation (EWI) at existing dwellings in Swansea. The EWI has been installed as a method of improving the energy efficiency of homes that are classified as being in the greatest need, due to high levels of deprivation and subsequent fuel poverty, within the local geographical community. All the homes are of traditional solid wall construction as they were built before 1919 and considered to have poor thermal performance as a result, which further exacerbates difficulties for occupants to pay their energy bills. The potential significance of the results of this research is unprecedented; this is due to the impetus for improving the energy efficiency of the UK's existing housing stock in recognition of their anticipated life expectancy and contribution to global carbon emissions.

In order to understand the research, first the background and context for the project is considered, which includes who has been involved in the research, how it has been funded, why it was necessary and the scope and limitations. Second the gaps in knowledge are explored, to which the project seeks to contribute to addressing. Third the aim and objectives of the project are explained; these define the purpose of the research. Fourth the contribution to knowledge has been discussed, which is fundamental to achieving the goal of adding to the expertise in the important field of improving the thermal performance of existing dwellings. Finally the structure of the thesis is set out to enable the reader to fully understand what is going to be discussed throughout this document.

## 1.1 Background and context

This section commences by discussing the organisations which have made the research possible by providing physical, financial and commercial support. This is then followed by an examination of the foundations, scope and limitations of the research project.

### *Organisations involved*

This research has been primarily funded by the Convergence West Wales and the Valleys Programme, which is managed by the Welsh European Funding Office who are an Executive Agency of the Welsh Government delivering the Knowledge Economy Skills Scholarship (KESS). KESS is led by Bangor University on behalf of the Higher Education Sector in Wales to support collaborative research, working with external partners based in the Convergence area of Wales (Bangor University, 2010). Support, in the form of KESS funding, was awarded from the European Social Fund to Cardiff Metropolitan University (CMU), which at the time was the University of Wales Institute, Cardiff (UWIC), on the 26th August 2009. The research has been undertaken within the Cardiff School of Art and Design at CMU, which commenced in August 2010. Additional funding and support has been provided by the Industrial Partner for the project, Coastal Housing Group (CHG) based in Swansea in south west Wales of the UK.

Coastal Housing Group is a Registered Social Landlord (RSL) providing affordable housing in the Swansea and Neath Port Talbot areas of south west Wales (CHG, 2010). CHG develop homes and communities for people of different ages and housing needs. In addition, CHG provide support services for those who require adaptation of their home, assistance in managing their tenancy, and for older people. As part of CHG's commitment to providing decent homes for their tenants, they continuously maintain and look at ways to improve their dwellings (ibid). The results of this research are expected to be exploited by CHG as part of their efforts to enhance the quality of life for their residents.

### *Project foundations*

This doctoral project was instigated following the award of funding to CHG through the first phase of the Welsh Government's Strategic Energy Performance Funding Programme, otherwise known as 'Arbed', which is the welsh word for 'save'. For the purpose of this thesis, this first phase is referred to as 'Arbed I' hereafter. Whilst the features of Arbed I are discussed in more detail in Section 2.3 of this thesis, the overall purpose of the scheme was to provide localised economic, social and environmental benefits through energy efficiency improvements at existing dwellings throughout Wales. One of the primary energy efficiency improvement measures installed through Arbed I was that of retrofitted EWI at traditional existing dwellings built before 1919.

A criterion of the Arbed I funding was that monitoring and evaluation had to be undertaken to determine the effectiveness of the improvement measures installed. However, there was limited funding and no methodology for these assessments. As a result, CHG collaborated with CMU to fulfil this criterion and subsequently developed this doctoral research project. Following discussions with a second housing association in Swansea, Family Housing Association (FHA), and CHG realised that they were not the only ones in the situation of having difficulties with fulfilling this criterion. These discussions led to the research project also involving case studies from FHA. Thus the heart of this research is centred on evaluating retrofitted EWI, which have been implemented by CHG and FHA through Arbed I in Swansea. The results of this evaluation are expected to contribute to filling some of the gaps in knowledge that have been identified in respect of improving the energy efficiency of traditional existing dwellings.

## 1.2 Gaps in knowledge

In expanding the research proposal for this project, which followed the initial cultivation between CHG and CMU, the significance of this doctoral research project was evident due to the gaps in knowledge. Whilst some of the literature discussed in this section has been written in the latter stages of this project (2013), and thus was not available at the outset to support the requirement for the research, it has been included here to demonstrate that the basis for the study was correct. However, Chapter Two, which discusses the motivation for the research is focused upon literature that was written and thus available at the early stages of the project (up to 2012) and therefore demonstrates that there was sufficient evidence to support the requirement for the study. The literature that is discussed in this section is then revisited in Chapter Six where it is discussed in detail in relation to that which is included in Chapters Two and Three.

> *Most of this [building evaluation] work has been about non-domestic buildings: there is little housing building evaluation*.
>
> Leaman *et al* (2010)

At the commencement of this study in August 2010, the evidence supporting further research was centred on the recognition that very little monitoring and evaluation of domestic buildings had been undertaken and a change in focus was required within the domestic sector of the UK construction industry (Department for Communities and Local Government, 2007a, Killip, 2008; Leaman *et al*, 2010). Furthermore, improving the energy efficiency of newly built homes had been the primary concern, rather than an equal balance with that of existing dwellings (DCLG, 2007a, Killip, 2008). This change in focus was attributed to the acknowledgment that existing dwellings accounted for the majority of domestic carbon emissions and not newly built homes (DCLG, 2008a; Killip, 2008). Since this research project commenced, the change in focus has continued to gain momentum to the extent that retrofitting existing dwellings, to improve their energy efficiency, appears to have become one of the most topical aspects of the construction industry.

One of the main drivers for this increased momentum appears to be the UK Government's Green Deal initiative and its Energy Company Obligation (ECO) counterpart, which was launched in October 2010 (DECC_2010a). However, as a result of an increased awareness of the requirement to improve the energy efficiency of existing dwellings, it has been recognised that there is a large gap in baseline data for the environmental and energy performance of traditional buildings[1], which represent approximately 25% of the UK's existing dwellings (Rye and Hubbard, 2012). These traditionally built dwellings are expected to be one of the main recipients of Green Deal and ECO funded work, with the latter primarily expected to fund retrofitted solid wall insulation (Sandell, 2013). Furthermore, Leaman *et al* (2010) state that there is a general lack of domestic energy use benchmark data, for different dwelling typologies and occupancies, within the UK, which further strengthens the argument for more data collection to be undertaken.

[1] A traditional building is classified as one that was built before 1919 with solid, moisture permeable walls (English Heritage, 2011).

Without any baseline data, improvements in energy efficiency cannot be accurately quantified, which could undermine the principles of initiatives such as the Green Deal (DECC, 2010a; Rye and Hubbard, 2012; May and Rye, 2012). Furthermore, May and Rye (2012) argue that the potential impacts of retrofit measures, such as those that will be installed through the Green Deal and ECO, on the fabric of traditional buildings are not fully understood. As a result, it is not known if the retrofit measures will have the desired effects or conversely create problems that will actually increase energy use, carbon emissions and fuel poverty (May and Rye, 2012). In addition, inappropriate retrofit measures to the fabric of traditional buildings could induce moisture problems that affect the health of occupants; for example damp and mould growth resulting from interstitial and internal surface condensation (English Heritage, 2010a; Roys *et al*, 2010).

Monitoring and evaluating retrofitted energy efficiency measures at existing dwellings is at the heart of establishing if the desired effects are actually being achieved. Initiatives, such as Arbed I and the Technology Strategy Board’s (TSB) ‘retrofit for the future’ scheme acknowledged the importance of these assessments (Welsh Assembly Government, 2010a; WAG, 2010b; Energy Saving Trust and BSRIA, 2012; Ruyssevelt, 2012; and Woosey, 2012). However, there are issues with both of these former initiatives in respect of providing representative data for schemes, such as the Green Deal and ECO. As discussed above, there was no methodology and very limited funding for the assessments through Arbed I, which has primarily resulted in a lack of empirical data for actual energy performance. Yet, it appears to the author that Arbed I provided a comparable ‘test bed’ for the Green Deal and ECO; this is due to the similar budgets available per dwelling.

With the TSB’s retrofit for the future scheme, the opposite was true. A detailed methodology for comprehensive monitoring and evaluation was set out, along with sufficient funding (Morgan, 2009; EST, 2009). Whilst the results of these assessments will provide valuable empirical data for demonstrating the effects of the retrofitted energy efficiency measures, the budget for each dwelling was up to 12 times that of the availability through the Green Deal, which has been set at a maximum of £10,000 per dwelling (Association of Energy Conscious Builders, 2011). Furthermore, two dwelling categories that are included in Arbed I were either lacking or non-existent in the TSB’s retrofit for the future scheme; these are dwellings with solid walls and located in west Wales, respectively (Ruyssevelt, 2012). Consequently, there remains a lack of empirical energy efficiency data in the literature that collectively encompasses these dwelling categories.

Whilst other retrofit initiatives assessed their projects, such as one of the Green Deal pilot studies ‘pay as you save’ in the east midlands region of England, the methods included the use of modelling tools[2] to ascertain improvements in energy efficiency (Maby, 2011). In addition, modelling tools have been used for assessing many of the other Arbed I projects across Wales (Woosey, 2012; Patterson, 2012). Thus, the outputs from these types of assessments have not addressed the lack of empirical data for the energy efficiency of existing

[2] In the UK, the Standard Assessment Procedure (SAP) and reduced data Standard Assessment Procedure (rdSAP) are the primary modelling tools used for assessing the energy performance of domestic buildings (DCLG, 2008a; King and Weeks, 2010).

dwellings. In particular, these projects have not contributed to knowledge, which is based on empirical data, about the energy performance of existing dwellings with solid walls and located in west Wales.

These modelling tools use a set of standardised parameters to assess the energy performance of dwellings and subsequently their accuracy is questionable (King, 2013). In particular, the standard modelling tool used to assess existing dwellings (rdSAP), which uses minimal quantities of data about the dwelling, has extensive limitations for accurately quantifying energy performance and subsequent costs (DCLG, 2008b). Therefore, in addition to not contributing accurate knowledge about the energy performance of existing dwellings, the use of modelling tools have resulted in a lack of empirical data in literature for the cost-effectiveness and actual payback of retrofitted energy efficiency improvement measures. This is particularly pertinent to the Green Deal.

One of the fundamental principles of the Green Deal is that the repayments for recovering the capital costs of the energy efficiency improvement measures are less than or equal to the financial savings on an occupant's energy bill (DECC, 2010a). However, if these calculations are based on limited 'modelled' data, there is a risk that the actual energy savings may not cover the costs of the Green Deal repayments. Hence, in the author's opinion, the use of empirical data should be a prerequisite for all retrofit installations that require the financial savings to cover the upfront capital costs, plus any interest incurred if this is obtained on a loan basis; thus allowing them to be recouped over the life of the improvement measures. Nevertheless, the collection of this data would require a straightforward methodology to be established and implemented as part of standard practice.

In recognition of the lack of straightforward methodologies within the literature for obtaining empirical data from evaluating retrofitted energy efficiency measures, which can be implemented routinely and at reasonable costs, the TSB set out a competition bid as a possible method of addressing this issue TSB, 2013). Furthermore, this competition aims to address the lack of practical methodologies for implementing the retrofit process, in particular outside the realms of the Green Deal (ibid). In addition to a lack of empirical energy performance data, the deficiency of methodologies for evaluating retrofitted existing dwellings appears to have resulted in limited published literature that documents what can go wrong on site, both before and during the retrofit process.

In particular, there appears to be a lack of published data that documents the impact of: minimal or non-existent pre-retrofit surveys, which can subsequently lead to a lack of appropriate technical designs and specifications, specifically for individual dwellings; and poor execution quality on site (Hopper, 2012; Hopper *et al,* 2012a; Hopper *et al*, 2012b). These issues are particularly significant to retrofitted EWI installations. Notably, this lack of data, which is specifically related to retrofitted EWI, has resulted in the author's published work (Hopper *et al,* 2012a; Hopper *et al*, 2012b) being cited in Phlorum (2012), May and Rye (2012) and BRE (2013). In addition, the author was requested to present findings from this aspect of the research project at the South East Wales Energy Partnership Housing Sub-Committee's meeting in July 2011, at the Society for the Protection of Ancient Buildings (SPAB) Technical Panel in June 2012 and the Wales Traditional & Sustainability Building Skills Advisory Group's conference in March 2014.

Finally, in addition to a lack of published data about energy performance, there is a lack of published literature, based on empirical data that documents the effects of occupant behaviour on traditional existing dwellings, following retrofitted improvement measures (May and Rye, 2012). Conversely, it is widely documented that one of the primary objectives that are required when evaluating the energy performance of dwellings is to establish if any energy savings are absorbed as a result of occupant behaviour, otherwise known as comfort ’take back’ or a form of rebound effect (National Audit Office, 2008; Love, 2012; Jankel, 2013). This is particularly pertinent in dwellings where occupants were in fuel poverty prior to retrofitted energy efficiency measures being installed (Boardman, 2007; National Housing Federation, 2012).

Collectively, these gaps in knowledge, which have continued to expand throughout the project, provide a rationale for research within the field of retrofitted energy efficiency improvement measures at traditionally built existing dwellings. Given the fact that the ECO counterpart of the Green Deal is expected to focus primarily on insulating solid walls, evaluating the impact of retrofitted EWI, both in terms of the energy performance of the dwelling and occupant thermal comfort is considered, by the author, to be crucial in enabling the momentum to continue and at the same time reduce risk of reprisal towards the energy efficiency retrofit industry. In order to move forward with this doctoral research project and thus contribute to filling these gaps in knowledge, an aim and corresponding objectives are required to ensure that the focus is pertinent.

## 1.3 Aim and Objectives of research

This section sets out the overall aim of the research and the objectives for achieving the aim. The aim and objectives of the research encompass the rationale based on the knowledge gaps identified in Section 1.2 above. In deciding whether the aim and objectives have been addressed, these are re-visited in Chapter Seven where the conclusions of this doctoral research project are set out.

### *Aim*

To investigate the link between the construction quality of retrofitted external wall insulation and the resulting impact on energy efficiency for existing dwellings in Swansea.

### *Objectives*

1. To appraise the implementation and execution of retrofitted external wall insulation for the Arbed I case study dwellings, to determine the effects on the quality of the installations.
2. To determine the value of and the need for non-invasive investigation techniques to confirm the construction quality and thermal integrity of retrofitted external wall insulation.
3. To assess the energy and carbon emission reductions together with the cost effectiveness of retrofitting external wall insulation at the Arbed I case study dwellings and identify any relationship to post-retrofit occupant thermal comfort perceptions and behaviour.
4. To determine the value of and need for empirical energy consumption data to confirm the energy performance of traditional dwellings that have received retrofitted external wall insulation.

## 1.4 Research problem

Based on the knowledge gaps discussed in Section 1.2, along with the aim and objectives set out in Section 1.3, an overarching research question has evolved, which has been divided into four specific sub-questions, to define the research problem that this research project seeks to address.

***Overarching research question***

*How effective was the retrofitted external wall insulation, in terms of quality and impact on energy efficiency at the Arbed I case study dwellings in Swansea?*

***Sub-question 1***

*What can be learnt from the method of implementation and execution of the retrofitted EWI at the Arbed I case study dwellings, which can be carried forward to improve future installations through other activities, such as the Green Deal?*

***Sub-question 2***

*Has the retrofitted EWI resulted in reduced energy consumption and thus carbon emissions at the Arbed I case study dwellings?*

***Sub-question 3***

*Is retrofitting EWI cost effective?*

***Sub-question 4***

*Are occupant thermal comfort perceptions and behaviour consistent with the energy consumption and cost-effectiveness results at the Arbed I case study dwellings?*

## 1.5 Scope

At the commencement of this research project (August 2010) the focus was upon collecting data from case study dwellings that received a range of improvement measures, which included: EWI; solar hot water panels; Photovoltaic panels; air-source heat pumps (off gas only); and micro combined heat and power. In assessing the effectiveness of these improvement measures, from both an occupant and thermal performance perspective, the data collection methods are centred on these social and physical factors. Thus at the outset of this project, the methods of data collection consisted of: desk-based studies to collect statistical data for the geographical community, along with relevant data held by the housing associations, such as location of case study dwellings and stock condition surveys; pre-retrofit and post-retrofit occupant surveys to establish occupancy levels and dwelling characteristics, end-uses of energy and annual consumption, occupant attitudes and behaviour towards energy, along with occupant thermal comfort perceptions; pre-retrofit and post-retrofit thermographic and air-tightness testing to assess fabric performance; and longitudinal studies of internal and external environmental conditions.

As discussed in Section 1.1 above, CHG and FHA are both based in Swansea and thus all of the data for this research project has been collected from case study dwellings located in this geographical area. Whilst the results from this research will be applicable to this geographical area, it is expected that the findings will be relevant to other locations in the UK where there are traditional solid wall dwellings and that have similar levels of deprivation. In addition, the coastal location and exposure to wind driven rain in Swansea mean that the case study dwellings for this project are subjected to some of the worst external environmental conditions that exist in the UK. Therefore, this geographical location could potentially provide a ‘worst case scenario’ case study for the impacts of retrofitting EWI to traditional existing dwellings in the UK.

Between CHG and FHA, approximately 200 dwellings in Swansea, which are a mix of publicly and privately owner-occupied, were to receive at least one retrofitted improvement measure through Arbed I. Both CHG and FHA were eligible to apply for Arbed I funding due to the high level of deprivation that exists amongst the communities where they own dwellings and thus likelihood of the occupants being in fuel poverty. The mechanism for identifying levels of deprivation was the income domain of the Welsh Index of Multiple Deprivation 2008 (WIMD). Based on the geography of Lower Super Output Areas (LSOAs), WIMD 2008 sets these areas in a ranking from one to 1896. The most deprived 10% LSOAs are those that are ranked between one and 190. The next deprived 40% (11% to 50%) are LSOAs that are ranked between 191 and 948 (Welsh Assembly Government, 2008a).

Swansea has 147 LSOAs and of these, 19 fall in the overall 10% most deprived areas in Wales (City and County of Swansea, 2011). Using data sourced from the Welsh Assembly Government (2008b) Figure 1 below illustrates the nine LSOAs where the Arbed I case study dwellings are located, along with their corresponding income domain ranking category within the WIMD 2008. The illustration in Figure 1 demonstrates that both CHG and FHA have focused their Arbed I work in some of the most deprived geographical areas of Swansea where they own properties. Furthermore, this data demonstrates the potential for the results of this research to represent a range of deprived communities from across Swansea. Nevertheless, the data collection for this project was not without limitations.

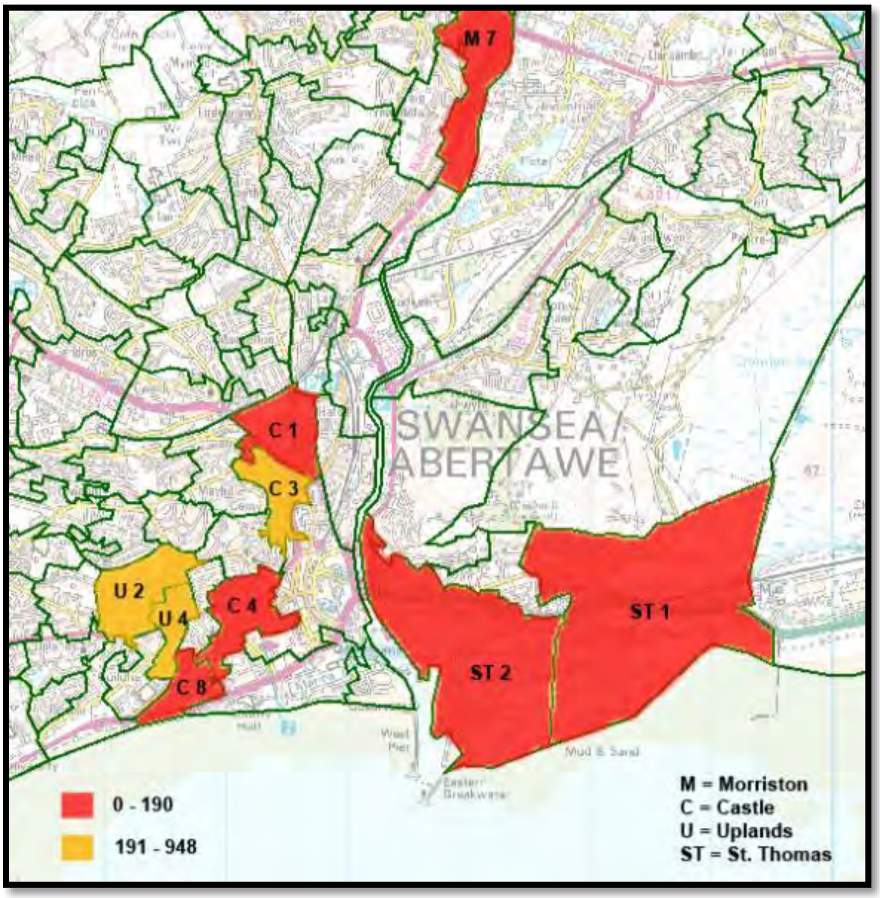


**Figure 1: Arbed I Lower Super Output Areas (based on the Income Domain categories of WIMD 2008): produced by the author**

## 1.6 Limitations

As with all research projects there were limitations imposed on the data collection. However, some of the limitations provided a natural focus for the research and prevented the study from becoming too broad. First and foremost the case study dwellings for this research were limited to those that were eligible for Arbed I subsidy, which were identified by CHG and FHA as part of their approved funding proposals. Furthermore, the study quickly focused upon one improvement method. EWI was the predominant retrofitted improvement measure installed by both CHG and FHA. In addition, retrofitted solid wall insulation (EWI and internal wall insulation) is expected to be one of the most sought after improvement measures to be funded through the UK Government's Green Deal initiative and the Energy Company Obligation (ECO) counterpart (Sandell, 2013). Therefore, with EWI being the dominant focus of this research, the findings are expected to be beneficial beyond this study.

The limitations imposed on data collection consisted of a mix of the availability of time, skills, resources and budget to undertake the physical monitoring activities, along with the response rate of occupants for the social aspects of the study. Part of the Arbed I funding criteria was that the retrofit work had to be completed by the 31st March 2011 and this research project commenced on the 9th August 2010. At the start of this doctoral research project, FHA was not involved in the research project and CHG, as the industrial partner, were still determining which dwellings to retrofit through an external (third party) organisation, which were to act as the project manager. As part of the initial assessments, the project manager was, at this stage, responsible for collecting the pre-retrofit thermal performance data[3] and then giving this to CHG. However, the availability and willingness of occupants to engage with the external organisation proved difficult to overcome. Thus, the data required to initiate the retrofit work was not obtained and collated until late September 2010.

Once the data was available and decisions made as to which dwellings to retrofit, CHG then had to initiate the procurement of the work; this was achieved through a Design and Build contract with a Principal Contractor, in addition to the project manager. At this stage CHG were able to provide the author with the details of

[3] The thermal performance data provided a basic appraisal of the dwelling to determine the requirement for retrofitted energy efficiency improvement measures. It did not provide the data required to establish actual thermal performance and thus this research did not duplicate the results.

the dwellings to allow contact to be made and thus initiate engagement with this research project. The retrofit work was undertaken in stages (one street at a time) and eventually commenced in December 2010. The author encountered the same issues of availability and willingness of the occupants, as the external organisation had previously. However, once occupants could see that the work was about to start on other dwellings; this improved the interest of the occupants to participate in this research project. This willingness of occupant cooperation was the ultimate determining factor for the quantity of case study dwellings available to evaluate for this doctoral research project. Nevertheless, there were many other factors that contributed to the limitation imposed on the data collection for this project.

Whilst pre-retrofit and post-retrofit air-tightness testing would have provided useful comparative data, along with longitudinal studies of external and internal environmental conditions, it was determined within the first few months of the project that these would not be viable. With the limited time and funding available, along with the lack of skills for undertaking both thermographic and air-tightness surveys, the author decided to focus on the former. The rationale for this decision was based on the scope of the potential outputs from the thermographic surveys being able to detect potential air-leakage pathways, together with potential heat loss. In addition, CHG also expressed an interest in purchasing and providing training for use of an infrared camera; this was for use on this and other research projects that they were involved in. However, despite these positive factors offered by CHG, the number of case study dwellings that could be surveyed using thermographic methods was limited by further factors.

Whilst occupants did not need to participate in the thermographic surveys, they did need to be willing to activate their space heating, keep their windows and doors shut and also allow the author to enter their home to take internal environmental readings, such as air temperature. In addition, due to the criteria for external environmental conditions (discussed in Chapter Three) there was a requirement for these thermographic surveys to be undertaken in the dark. This usually meant unsociable times of the day, and the potential for arrangements to have to be changed at the last minute. Having to undertake the surveys in the dark and enter the homes of strangers meant that the author could not work alone and therefore needed to be accompanied; thus requiring the availability of an accompanying person being required. Furthermore, any rearrangements due to inappropriate weather immediately before any planned survey subsequently meant that the availability of both the occupant and the 'accompanying person' was not always possible. Collectively, these requirements imposed further significant limitations on collecting thermographic data for the project.

Limited time and funding was the rationale behind the decision not to undertake the longitudinal studies of external and internal environmental conditions. The potential number of case study dwellings and their geographical distribution across Swansea meant that the costs of the equipment to monitor the environmental conditions were beyond the scope of the project. However, to overcome the limitations imposed by the potential omission of external environmental conditions it was decided that the author would make use of, and thus download this data from the City and County of Swansea website (City and County of Swansea, 2011 and 2013). This website provides an extensive and detailed record of external environmental data for much of Swansea.

In terms of the occupant surveys, a fellow researcher at CMU attempted to undertake postal questionnaires for their research project at some of the same Arbed I case study dwellings. However, the response from just one occupant, meant that the author needed a different approach (which is discussed in Chapter Four of this thesis). Nevertheless, for this doctoral research project there were further limitations imposed by occupants' willingness to participate in the research. These limitations included occupants' lack of time availability and further still by their limited knowledge and awareness, which hindered their ability to provide the information requested of them in the questionnaire. In addition, many occupants either did not keep their energy bills or had a prepayment meter and thus had no record of their energy use. Upon discovering this significant issue with collecting energy data, as part of the pre-retrofit occupant surveys, this was overcome with reasonable success by including a consent form, at the post-retrofit stage, for direct contact to be made with energy suppliers to obtain this data.

However, there were still some issues with incorrect information being given by the occupants, which led to the omission of energy data from some of the case study dwellings. Furthermore, despite consent being given by the occupants many of the energy suppliers took an extremely long time (up to six months) to provide the data. Other energy suppliers failed to provide any data at all. One of the most significant impacts this lack of data had was that a domestic energy use benchmark could not be established as an output from this doctoral research project. As discussed in Section 1.2 above and 3.1 below, this type of benchmark does not exist for domestic buildings and it was intended that a contribution could be made to filling this knowledge gap. Nevertheless, the pre-retrofit and post-retrofit energy use data that has been collected through this research will make a significant contribution to knowledge and understanding of the impact that retrofitted EWI has on overall energy efficiency and fuel poverty for traditional domestic dwellings.

## 1.7 Contribution to knowledge

In meeting the aim and objectives of this research, within the scope and limitations set out in Sections 1.5 and 1.6 above, this doctoral research project has made a significant and original contribution to the body of knowledge by providing both methodological processes and empirical data in respect of evaluating retrofitted EWI at traditional existing dwellings. Set out below are four main outputs from the research, which are split between the two overarching categories. This is then followed by a discussion of the dissemination of early findings that has already taken place, which includes five peer-reviewed publications.

This case study makes a contribution to knowledge by filling some of the gaps in knowledge about the effectiveness of retrofitted EWI at traditional dwellings in south west Wales. The gaps in knowledge that this doctoral research project has contributed to filling are:

### *Methodologies*

#### Contribution 1:

A METHODOLOGY FOR SIMULTANEOUSLY OBTAINING EMPIRICAL DATA ABOUT THE CONSTRUCTION QUALITY AND ENERGY PERFORMANCE OF TRADITIONAL DWELLINGS RECEIVING RETROFITTED EWI

#### Contribution 2:

A METHODOLOGY FOR ASSESSING THE CONSTRUCTION QUALITY OF RETROFITTED EWI, WHICH CAN BE USED AS PART OF UNDERTAKING THE QUALITY CONTROL PROCESS FOR FUTURE INSTALLATIONS

### *Empirical data*

#### Contribution 3:

EMPIRICAL BASELINE ENERGY PERFORMANCE DATA FOR TRADITIONAL DWELLINGS IN SOUTH WEST WALES

#### Contribution 4:

AN EWI RETROFIT CASE STUDY, WHICH PROVIDES SIMULTANEOUS EMPIRICAL CONSTRUCTION QUALITY AND ENERGY PERFORMANCE DATA FROM TRADITIONAL DWELLINGS IN SOUTH WEST WALES, WHICH ALSO DOCUMENTS WHAT CAN GO WRONG ON SITE, ALONG WITH THE LESSONS LEARNT

### *Dissemination*

As discussed in Section 1.2 above, the author has already commenced making a contribution to the body of knowledge during the project through a number of peer-reviewed publications documenting some of the early key findings from this research project. The main publication that reinforced the significance of this research, and which catapulted it into the awareness of many high profile professionals within the retrofit industry, is the ‘Retrofit 2012’ conference paper (see Appendix III), entitled: *Assessing the execution of retrofitted external wall insulation for pre-1919 dwellings in Swansea (UK).* Following the presentation of this paper in January 2012 at the Retrofit 2012 conference, the author was invited to form part of an Expert Panel Meeting on Thermal Insulation and Storage Materials. The meeting was held at the Department for Communities and Local Government offices in London in February 2012 (Cooper and Palmer, 2012).

In addition, the author was invited to present an overview of the Retrofit 2012 conference paper at the SPAB Technical Panel meeting in June 2012. The purpose of the SPAB Technical Panel meeting was to discuss the potential implications and impacts of the Green Deal on traditional buildings. During the meeting, May (2012) presented the early key findings of a gap analysis that was being undertaken by the Sustainable Traditional Buildings Alliance (STBA), which has since been published (see May and Rye, 2012). The gap analysis of previous and current research on the thermal performance of existing and retrofitted traditional buildings, which was endorsed by DECC, involved categorising published work into four tiers of significance. The results of the gap analysis identified very little research that lay within tier one, which represented the most significant data and knowledge. However, May (2012) referred to Hopper *et al* (2012a) and this doctoral project as being one of the few research studies that did lie within tier one.

Prior to the Retrofit 2012 conference, the author had published two conference papers, which introduced the research project by setting the scene for the data collection methods, based on early reviews of literature (Hopper *et al*, 2011a; Hopper *et al*, 2011b – see Appendix I and II, respectively). Following the Retrofit 2012 conference paper, the author had a journal paper published (Hopper *et al,* 2012b – see Appendix IV). This journal paper documented some early results from the research. Furthermore, the author contributed to CMU's Research Review 2012 publication as a co-author with another doctoral scholar (see Appendix V). The author was also awarded 'Highly Commended' for the Chartered Institute of Architectural Technologist's (CIAT) 2012 annual Student Award Technical Report competition (Appendix VI). Finally, the author was invited to contribute a case study book chapter for CIAT (Appendix VII). The book was edited by Emmitt (Hopper, 2013) and entitled: *Architectural Technology: Research and Practice.* The case study provided a summary of some of the early findings from this research and was written from the perspective of being an Architectural Technologist working within the UK retrofit industry. Collectively, these publications demonstrate some early original and significant contributions to knowledge as a result of the research that has been undertaken for this doctoral project.

## 1.8 Structure of Thesis

Building on this Chapter (One) with a critical review of existing literature, Chapters Two and Three set the scene for this doctoral research project. Chapter Two reviews existing literature for energy, policy and occupants regarding existing dwellings and thus identifies the gaps in knowledge; these continue to create an argument for the need for this research and also where contributions to knowledge can be made. Chapter Three reviews existing literature that discusses building performance evaluation techniques to explore the options for data collection methods, which informed the overall methodology. Chapter Four sets out the adopted methodology for the doctoral research project, including the aim and of objectives. Chapter Four includes defining the research problem, justifying the research approach and the data collection and analysis methods. Chapter Five documents the results by setting out the data that was collected; these are grouped into two main sections: construction quality and energy performance. Chapter Six discusses the findings in relation to the gaps in knowledge identified in the literature review. Finally, Chapter Seven sets out the conclusions of this doctoral research project.

# Chapter 2: Energy, Policy and Occupants: Existing Dwellings

# Chapter 2: Energy, Policy and Occupants: Existing Dwellings

This chapter sets the scene for this study by reviewing literature that supports the requirement for this doctoral research project. Commencing with setting out the overarching drivers for improving the energy efficiency of existing dwellings, the review then narrows with an examination of the UK's dwelling stock to provide context for the study. This is then followed by an appraisal of the policy drivers and strategies for improving the energy efficiency of existing dwellings in England and Wales, which leads onto a review of the challenges related to making these improvements.

## 2.1 Rationale for improving the energy efficiency of existing dwellings

The requirement to improve the energy efficiency of existing dwellings is driven by three overarching objectives: mitigating and adapting to climate change; maintaining energy security; and eradicating fuel poverty. Whilst each objective poses specific and unique challenges, there are potential synergies from taking an amalgamated approach to addressing these complex global and national issues (NAO, 2008; Hopper *et al*, 2011a; Coyne, 2012). This section discusses each of these objectives in turn to provide the reader with an overview of the eminence for this research.

### *Climate Change*

The consensus of scientific evidence that the global climate is changing is unequivocal and it is claimed that there is a greater than 90% probability that this is anthropogenic (Intergovernmental Panel on Climate Change, 2007a). The increased accumulation of greenhouse gases in the atmosphere is amplifying the natural greenhouse effect and causing: the air and sea temperatures to rise; snow and ice to melt; and sea levels to rise (H.M. Government, 2006; IPCC, 2007b). The science suggests that an increased global temperature of more than 2°C will bring about irreversible and catastrophic changes to the planet's ecosystems and thus its ability to support all plant, animal and human life (Stern, 2006; IPCC, 2007a). In addition, it has been argued that these changes will have a significant negative effect on the global economy, further exacerbating the impact on human societies (Stern, 2006).

Chiefly, the greenhouse gas that is bringing about these changes is carbon dioxide, which for over the last 100 years, since the industrial revolution, has been increasing to levels beyond the natural balance within the atmosphere (H.M. Government, 2006; IPCC, 2007b). As a result of these changes, the climate projections for the UK include hotter and drier summers, wetter winters and more extreme weather events (Murphy *et al*, 2009). The main anthropogenic cause of increased levels of atmospheric carbon dioxide is burning fossil fuels to generate energy (IPCC, 2007b). In response to this compelling scientific evidence, the UK Government have set legally binding targets to reduce carbon dioxide emissions (carbon emissions hereafter). The Climate Change Act 2008 stipulates an 80% reduction in carbon emissions by 2050, based on the 1990 baseline, with an interim target of a 34% reduction by 2020. However, it has been argued that these targets are not enough to prevent catastrophic changes to the climate. In Wales, the Welsh Government has set a 3% reduction target for the carbon emissions for which they have devolved responsibilities (Welsh Government, 2010e).

With dwellings accounting for approximately 27% of UK carbon emissions, it has been recognised that the domestic sector can make a significant contribution to these mandatory reductions (Defra, 2007). Whilst newly built dwellings are designed and constructed with consideration to climate change, it has been acknowledged that there is an urgent requirement to adapt existing dwellings for both the future climate and to reduce carbon emissions resulting from their use (Killip, 2008; Gething, 2010). The UK has some of the oldest, and thus least energy efficient dwellings in Europe (Building Performance Institute Europe, 2011; Gleeson, 2011). In addition, it has been documented that over two thirds of existing dwellings are expected to still be in use in 2050 (DCLG, 2008a; BRE, 2011). Therefore it can be argued that there is no choice about addressing the energy efficiency of existing dwellings. However, reducing carbon emissions is not the only issue related to existing dwellings and their elevated energy consumption. There is also the issue of energy security, which thus provides an additional driver for reducing energy consumption from existing dwellings.

### *Energy security*

Energy security is defined as *"the availability of sufficient supplies at affordable prices"* (Yergin, 2006). However, the UK faces increased risks and significant challenges if it is to maintain the level of energy security that it has enjoyed for several decades (BERR, 2008a). These challenges are as a result of dwindling fossil fuel reserves, along with mandatory power station closures and requirements to use alternative sources of supply that do not impact on the natural environment (ibid). The UK's North Sea oil and gas reserves peaked in first decade of this millennia and as a result have been a net importer of these fossil fuels since 2004 (DECC, 2010b). These reserves were the primary reason that the UK has enjoyed such high levels of energy security (BERR, 2008a). Consequently, the UK is becoming ever more reliant on imported fuels and thus is increasingly vulnerable to disruptions of energy supply (DTI, 2007).

In addition to increasing supply from renewable sources, one of the main foci of ensuring future energy security, is reducing demand through improved end-use efficiency (Defra, 2007; NAO, 2008; European Union, 2011). However, this is a difficult challenge to overcome as overall demand increases. Despite global energy policies to reduce energy consumption, the IEA have forecast an international increase in energy demand to the year 2035 (IEA, 2010). Not only are countries with an already high level of consumption increasing their demand, such as the UK and the USA, other countries such as India and China are also increasing their energy use at a formidable rate. The main reason for India and China's increased energy consumption is their high rate of economic growth (Yergin, 2006).

In the UK, the domestic sector accounts for around 28% of all energy consumed, which is second only to transport (DECC, 2010b). Accounting for around 60% of this domestic energy use, space heating has a significant impact on overall consumption and thus demand within the UK. In 2010, it was calculated that domestic energy use had increased by 18% between 1970 and 2009. This increase correlates with an average increase of around 5.0°C for internal temperatures within dwellings (DECC, 2010c). However, as demonstrated in Section 2.2 below, overall energy consumption in the UK could have been much higher had some improvements in energy efficiency not occurred during the same period (ibid). It can therefore be concluded that if energy demand for space heating is reduced, this could have a significant impact on both meeting climate change targets and increasing energy security in the UK. Furthermore, these energy efficiency improvements should make a significant contribution to alleviating fuel poverty within the most vulnerable dwellings.

### *Fuel poverty*

The main factors that are attributed to fuel poverty are household income, thermal performance of dwellings and fuels costs (Palmer *et al*, 2005). The definition of fuel poverty is where more than 10% of household income is spent on energy use to provide adequate heat in the dwelling (BERR, 2008b; Hirsch *et al*, 2011). Therefore, the higher fuels costs are and the lower household income is, the greater the risk there is of occupants being in fuel poverty (Herbert and Mackellow, 2010). In addition, there is a direct correlation between the age and type of dwelling and energy performance. Thus occupants who live in older and detached dwellings are more likely to be in fuel poverty (Howarth, 2010).

The UK and devolved administrations have each set a target for eradicating fuel poverty. In England the target year is 2016 and for Wales it is 2018 (BERR, 2008b). However, as fuel costs continue to rise at a much greater rate than household income, the number of fuel poor dwellings in the UK is climbing rather than reducing (BERR, 2008b; Herbert and Mackellow, 2010). This trend has continued since 2004. In 2006 there were one million more households in fuel poverty compared to the previous year, bringing the UK total to approximately 3.5 million, which represented just over 13% of all dwellings (BERR, 2008b). In Wales the magnitude of fuel poverty is even greater. Around 27% of households are thought to be in fuel poverty in Wales, which is just over double the UK average (Howarth, 2010). These statistics are a direct reflection of the age and energy performance of dwellings in Wales and thus go some way to explain the later target for eradication.

## 2.2 Existing dwellings: the context of UK stock

The enormity of the challenge for reducing carbon emissions, energy use and fuel poverty within existing dwellings is reflected in the UK dwelling statistics, which are discussed in this section. Predominantly this section examines the English and Welsh dwelling stock by discussing these dwelling statistics in terms of the characteristics that are directly relevant to these challenges. Where data is available, the Scottish dwelling stock is also discussed. These characteristics include quantity, type, tenure, age, and energy performance of existing dwellings. This section then concludes by considering the impact that poor energy performance has on society.

In 2008 there were approximately 26.2 million dwellings in the UK, of which around 22.4 million were in England, 2.5 million were in Scotland and 1.3 million were in Wales (Caunt, 2009; Randall, 2011). Where the data is available, the composition of dwelling types and tenures as of 2008 are set out in Table 1 and 2 below, respectively. Proportionally Wales has more houses or bungalows than flats compared to England and Scotland, which are made up of detached, semi-detached and terraced properties (ibid). In terms of tenure, Wales has a higher than UK average proportion of owner-occupied dwellings and lower that are rented, both from private and social landlords. However, according to Howarth (2011) these statistics had changed by March 2010 to 70%, 14% and 16% for owner-occupied, private rental and social rental tenures, respectively. Whilst, it is not discussed in literature (Caunt, 2009; Randall, 2011; Howarth, 2011) why these figures have changed, it is plausible to assume that the recession is a contributory factor. The recession is also a credible reason for the slowdown of building new dwellings in the UK.

**Table 1: Dwelling types in England, Scotland and Wales (given as percentages)**

| | | England | Scotland | Wales |
|---|---|---|---|---|
| Type | Flats / Maisonettes | 18.5% | 23% | 10% |
| | Houses / Bungalows | 81.6% | 77% | 90% |
| House / Bungalow type | Detached | 22.5% | - | 27% |
| | Semi-detached | 29.2% | - | 30% |
| | Terraced | 29.9% | 22% | 32% |

Source: Randall (2011)

**Table 2: Tenures in the UK and Wales (given as percentages)**

| Tenure | UK (average) | Wales |
|---|---|---|
| Owner-occupied | 69% | 73% |
| Rented (private) | 12.9% | 10% |
| Rented (Social) | 18.1% | 17% |

Source: Randall (2011)

The peak number of new dwellings that were built per year in the 20 years to 2010, within the UK, was between the years 2006 and 2007 and stands at 219,000 dwellings. For England the peak year was 2007 to 2008 when 169,000 new dwellings were built and for Scotland it was 26,500 between 2004 and 2005. In Wales 11,000 new homes were built in the peak year. However, this was between 1989 and 1990, which is significantly longer ago than for the rest of the UK (Randall, 2011). The number of newly built dwellings is also reflected in the age composition of UK stock. The age composition of dwellings for England and Wales, as at 2004, are set out in Table 3 below (this is the latest data available at the time of writing this doctorate thesis in 2013/ 2014). Due to the different sources of information used to compile Table 3, the author has grouped the data according to the dates available to allow a direct comparison to be made. In addition, the author has rounded the figures for Wales to the nearest 100 for quantity and whole number for the percentages to correspond with the presentation of data for England.

**Table 3: Age composition of dwellings in England and Wales (2004)**

| | England | | Wales | |
|---|---|---|---|---|
| **Age** | **Quantity** | **Percentage** | **Quantity** | **Percentage** |
| **Pre-1919** | 4,400,000 | 22% | 440,000 | 34% |
| **1920 – 1944** | 3,600,000 | 18% | 155,000 | 12% |
| **1945- 1964** | 4,200,000 | 20% | 249,500 | 19% |
| **1965 – 1980** | 4,400,000 | 22% | 242,500 | 18% |
| **Post-1981** | 3,600,000 | 18% | 218,000 | 17% |
| **Total** | 20,200,000 | 100% | 1,305,000 | 100% |

Source: for England, DCLG (2006); for Wales, Welsh Assembly Government (2005) and King (2011)

As shown in Table 3, the percentage of dwellings built in England and Wales after the Second World War (1945 onwards) are very similar. However, the figures before this time were quite different. Proportionally Wales has significantly more pre-1919 dwellings than England. Less than one quarter of dwellings in England were built before 1919, whereas over a third in Wales fit into this category. The significance of the number of dwellings that were built before 1919 is due to the majority of their construction type being of solid walls, which means they do not have a cavity and thus classified as hard-to-treat (this category is discussed in more detail in Section 2.4 below). The approximate number of traditional dwellings in the UK with solid walls is seven million, which represents approximately 27% of the total stock (Sustainable Development Commission, 2006; Green Building Council, 2008). In England and Wales traditional dwellings constructed with solid walls represent approximately 25% and 30% respectively

(NAO, 2008; EST, 2011). Collectively, these age and construction type figures are a reflection of the overall energy performance of dwellings in England and, in particular, Wales.

As discussed in Hopper *et* al (2011a) with reference to King and Weeks (2010), the energy performance of dwellings in the UK is measured using the Standard Assessment Procedure (SAP) methodology, which is based on energy use and costs for space and water heating, ventilation and lighting, minus savings made from technologies that generate energy. SAP provides a rating, ranging from one to 100, with the latter representing the most efficient energy performance. The methodology takes account of the heating system, thermal performance of the fabric, along with other factors such as: type of construction; building shape, size and orientation; and window size and distribution (DCLG, 2008a). SAP is predominantly used for assessing compliance with Part L1 of the Building Regulations and this is primarily for new dwellings (H.M. Government, 2010b). For existing dwellings, a reduced data version of SAP (rdSAP) is used.

Chiefly, rdSAP is used to produce Energy Performance Certificates (EPCs), which are required for all dwellings at the point of sale and lease (DCLG, 2008a). An EPC provides an energy and carbon emission performance rating on a scale from A to G, where A represents the highest efficiency (DCLG, 2008a; Energy Saving Trust, 2010). In 2004 approximately 66% of dwellings in the UK had an EPC rating between E and D, which correlates to a SAP rating of between 41 and 70 (DCLG, 2006a; EST, 2010a). The average SAP rating in England in 2008 was 51, which increased from 42 in 1996. In Wales the average SAP rating was 46 and 50 in 2004 and 2008, respectively (DCLG, 2006a). However, approximately

17% of dwellings in the UK have the lowest F and G ratings (EST, 2010b). According to the EST (2011), 40% of these dwellings are located in Wales.

All G and most F rated dwellings with a SAP rating of 30 or below qualify as a Category One Hazard for Excess Cold under the Housing Health and Safety Rating System (HHSRS) (Boardman, 2007). The purpose of the HHSRS is to provide a hazard severity rating for identified risks as a method of ensuring the health and safety of occupants and visitors of a dwelling (Decent and Safe Homes, 2007). Category One Hazards are the most severe and pose a significant risk to the health of occupants and increased chances of being in fuel poverty (Howarth, 2010). Approximately 11% of dwellings in Wales are classified as a Category One hazard for Excess Cold; this is compared to around 9% in England (Davidson *et al*, 2011).

In addition to these dwellings with a Category One hazard posing a health and safety risk to occupants and visitors, they also result in a significant financial cost to society due to the costs imposed on the National Health Service (NHS). It has been calculated that Category One Hazards for Excess Cold costs the NHS in excess of £21.4 million each year with care having to be provided for the most serious outcomes. These outcomes include death, heart attacks, respiratory disease and pneumonia (Nicol *et al*, 2010). However, there are a number of policy drivers and strategies that have the potential to improve the energy efficiency of existing dwellings and thus reduce the likelihood of these risks to society. Nevertheless, these drivers and strategies have their limitations, which have an impact on the results they achieve.

## 2.3 Policy drivers and strategies for improving the energy efficiency of existing dwellings in England and Wales

Until the launch of the Green Deal in October 2010 the focus for improving the energy efficiency of UK dwellings was very much on new build, rather than those that were already in existence (DCLG, 2007a, Killip, 2008). As discussed in Hopper *et* al (2011a), the main UK legislative driver for improving the energy efficiency of existing dwellings comes from a European level in the form of the Energy Performance in Buildings Directive (2010/31/EU), which is implemented through Part L1B of the Building Regulations and sets out the requirement for Energy Performance Certificates (European Parliament and the Council of the European Union, 2010).

In addition, the UK Government and devolved administrations have set minimum standards for dwellings. In England this is the Decent Homes standard and in Wales it is the Welsh Housing Quality Standard (Baxter, 2008). Whilst each of these drivers has the potential to drive improvements in energy efficiency, there are limitations for what they appear to be able to achieve. This section examines each of these drivers in turn. This is then followed by a review of the two main funding strategies that have been implemented in Wales and the UK as methods of improving the energy efficiency of existing dwellings; these are Arbed and the Green Deal, respectively.

### 2.3.1 Building Regulations

Part L1B of the UK Buildings Regulations (Conservation of fuel and power in existing dwellings) make requirements for energy performance improvements where there is work undertaken to energy related services and thermal elements (floors, walls and roofs). For thermal elements, minimum standards for heat loss are stipulated as U-Values where renovation work is undertaken that involves more than 50% of the external element or 25% of the entire external envelope (H.M. Government, 2010a). Renovation of thermal elements is conveyed as the provision of a new layer or the replacement of an existing layer. These layers could include cladding, rendering, plastering or dry-lining a thermal element, such as an external wall. Therefore, for example if at least 50% of the internal surface of an external wall within a heated room was to be dry-lined with plasterboard, then it is required that sufficient insulation is added to achieve a U-Value of 0.30 $W/m^2K$ where internal or external wall insulation is installed or 0.55 $W/ m^2K$ where cavity wall insulation is to be installed (ibid).

Whilst Part L1B of the Building Regulations stipulates heat loss reductions depicted as U-Values, the energy performance of existing dwellings is predominantly assessed using rdSAP, as discussed in Section 2.2 above. These rdSAP assessments are based on models and therefore use standardised assumptions for heat loss, which are based on the construction type of the thermal element. For example, the assumed U-Value for all solid walls is 2.1 $W/m^2K$ (Rhodes, 2007). Therefore calculations to determine reductions in heat loss are predominantly based on these assumed U-Values. However, where in-situ U-Value calculations have been undertaken, the results of these studies indicate a significant variation from the assumed ‘modelled’ figures (Stafford *et al*, 2011; Baker, 2011; Rye, 2011). As a result, not only are assessments for the improvements not accurate and thus lead to misleading results, they could lead to incorrectly specified insulation materials in terms of thermal performance (DCLG, 2008b). In addition, this could lead to inappropriate work being undertaken, for example installation of a high performance and impervious insulation materials, which could be detrimental to the existing fabric (English Heritage, 2011b).

Nevertheless, all improvements in thermal performance are only required where it is "*technically, functionally and economically feasible*" and can "*achieve a simple payback of 15 years or less*" (H.M. Government, 2010a). In addition, there are exemptions and situations where "s*pecial considerations*" result in a lesser thermal performance being required (ibid). Historic buildings, which include those that are listed, in conservation areas and scheduled monuments, are exempt from complying with Part L of the Buildings Regulations in situations where conforming would be detrimental to the character and appearance of the building. Special considerations are applicable where buildings have a historical interest due to their listing in local development plans or location within special areas, such as National Parks or within the curtilage of scheduled monuments (H.M. Government, 2010a; English Heritage, 2010b). Furthermore, special considerations are applicable for *"buildings of traditional construction with permeable fabric that both absorbs and readily allows the evaporation of moisture"* (H.M. Government, 2010a).

Whilst these traditional and historic buildings have lesser requirements or exemption, respectively, for compliance with Part L of the Building Regulations, improvement in their thermal performance is still advocated and undertaken without fully understanding the implications, particularly for traditional constructions (Stafford *et al*, 2011). For example, as discussed in Hopper *et al* (2011b), Garbutt (2008) argues that one of the most important selection criteria for insulation materials is the potential energy savings resulting from their installation. This argument has resulted in recommendations for fabric upgrades and thus manufacturers focusing on supplying insulation products with the lowest thermal conductivity values possible (EST, 2006; Shore, 2008). As a result, the EST (2006) and Thorpe (2010) highlight that the most commonly used insulation materials in the UK are fossil fuel derived rigid boards (such as Phenolic foam) and mineral glass fibre batts.

The latter mineral fibre based insulation materials have some of the vapour permeability properties required for upgrading traditional porous building fabrics. However, neither of these insulation materials have the hygroscopic properties required to maintain the ‘breathability’ of traditional porous building fabrics (ibid). Without the ability to maintain breathability, the existing fabric of the building, as well as the insulation, is at risk of becoming moist as a result of damp or interstitial condensation. When these rigid boards and mineral batts become wet they lose their insulating merits and trap this moisture within the fabric of the building; thus conversely reducing the thermal performance of the existing thermal element and risk degrading the structural integrity of the building (English Heritage, 2010a; May, 2005). The whole purpose of Part L1B of the Building Regulations is to reduce energy use and carbon emissions by setting out requirements to improve the thermal performance of existing dwellings. Nevertheless, if insulation materials without the necessary breathability properties are used, there is a risk that the opposite will occur.

In summary, Part L1B of the Building Regulations has the potential to make a significant contribution to improving the energy efficiency of existing dwellings. Nevertheless, there appears to be a considerable risk that this key legislative driver is not appropriate for a sizeable proportion of the UK housing stock. This is due to the apparent: lack of accurate baseline U-Values to assess improvements in thermal performance; lack of guidance for avoiding thermal bridging and improving air tightness; and use of inappropriate insulation materials at traditionally constructed dwellings. Furthermore, as set out in Hopper *et al* (2011a), compliance with the Building Regulations is a legal requirement and therefore should be enforced. Yet, enforcement and even prosecutions for non-compliance are virtually nonexistent. The primary reason for this lack of enforcement is that Part L of the Building Regulations is not considered a priority by Building Control Officers (Chartered Institute of Housing, 2007). A Building Control Officer's responsibility is to ensure compliance with the Building Regulations. In addition, Part L of the Building Regulations set out the requirement for the provision of EPCs. However, the provision of EPCs is enforced and thus has the potential to make a contribution to the improvement of energy efficiency within existing dwellings.

### 2.3.2 Energy Performance Certificates (EPCs)

As discussed in Hopper *et al* (2011a) and in Section 2.2 above, the provision of EPCs is mandatory at the point of sale or lease of a dwelling. The EPC sets out the energy and carbon emission performance of a dwelling at the time of the assessment, as well as the potential ratings that could be achieved if the series of cost-effective recommendations, which are also set out, are undertaken (Boardman, 2007; DECC, 2010d). Whilst the provision of an EPC is mandatory, following the recommendations is not. Furthermore, the Existing Homes Alliance (2010) argues that many occupants are not aware of the EPC when they purchase or lease their home. Where occupants are aware of the EPC, many find it difficult to understand and relate the information to their personal circumstances (ibid).

As well as to provide an existing and potential energy performance rating for a dwelling, the purpose of the EPC is to encourage dwelling owners to improve the energy efficiency and thus reduce carbon emissions by following the recommendations. However, it is argued that the EPC is just a rating system by itself and this is unlikely to drive improvements in energy efficiency (Boardman, 2007). This is particularly likely where the EPC is not fully understood, or worse not even acknowledged. In addition, the slow rate at which dwellings are sold in the UK mean that it is unlikely that an EPC will be produced for every owner-occupied home before 2050, further devaluing the scope of this driver to improve domestic energy efficiency (Boardman, 2007; Green Building Council, 2008).

For the EPC assessment, this is undertaken using rdSAP, which is designed to provide a like for like comparison between similar dwellings by making certain assumptions about the occupancy. These assumptions are based on a ‘standard occupancy’, whereby seasonal space heating is used for 9 hours a day from Monday to Friday and for 16 hours per day on Saturdays and Sundays, with internal temperatures of 18°C for all rooms except the main living rooms where there is an internal temperature of 21°C (Energy Reporter, nd; AECB, 2011).

However, it is widely documented in literature that the results of rdSAP calculations are unreliable and there are concerns for its use as a method of advising occupants about their current and potential energy use, particularly for traditional pre-1919 existing dwellings (English Heritage, 2007; DCLG, 2008a). These concerns are due to the high number of assumptions that are used in the calculations. In addition, the dynamic thermal performance of the wide variety of fabric constructions that were used to build these traditional dwellings are not accounted for in either SAP or rdSAP (ibid). Nevertheless, rdSAP is the adopted methodology used as the basis for assessing the thermal performance for all types of existing dwellings, including the energy efficiency category of the Welsh Housing Quality Standard.

### 2.3.3 Decent Homes and Welsh Housing Quality Standard (WHQS)

In recognition of the poor physical condition of so many existing dwellings in England and Wales, the UK Government and Welsh Government, respectively, set standards for making the necessary improvements by a given date. In England the Decent Homes standard had a target date of the end of 2010, whilst the Welsh Quality Housing Standard (WHQS) has to be achieved by the end of 2012 (Baxter, 2008). Whilst the Decent Homes standard is required to be met by an earlier date than the WHQS, the start date of the two standards was quite different. The Decent Homes standard was established in 1997, whereas the WHQS was in 2002 (DCLG, 2006b; HouseMark, 2008). Although there was an extra three years to achieve the Decent Homes standard, there are significantly more dwellings in England compared to Wales. However, it could be argued that due to the proportional older stock, as discussed in Section 2.2 above, and thus likelihood of having a greater number of dwellings that are in a poor physical condition, that Wales would need longer to achieve the WHQS.

In addition, whilst there are many similarities between the two standards, there are a number of differences, which could be argued to have both a positive and negative impact on their potential scope. In England, the Decent Homes standard applies to 100% of public sector dwellings and has also been targeted at 70% of vulnerable households in the private sector (NAO, 2010). Whereas in Wales, the WHQS only applies to all dwellings in the public sector (Baxter, 2008). The result of these two differences means that more dwellings are required to achieve the Decent Homes standard in England. However, in Wales the WHQS encompasses more criteria than the Decent Homes standard in England. In addition to standards for the physical condition of dwellings, the WHQS incorporates targets for social, environmental and economic awareness (ibid). Table 4 below sets out the categories for the two standards and thus demonstrates the additional requirements under the WHQS compared to the Decent Homes standard.

**Table 4: Decent Homes and WHQS target categories**

| **Decent Homes** (DCLG, 2006b) | **WHQS** (HouseMark, 2008) |
|---|---|
| • Minimum standard for housing (must not contain any Category 1 hazards under the HHSRS)<br>• In a reasonable state of repair<br>• Have reasonably modern facilities and services<br>• Provide a reasonable degree of thermal comfort | • In a good state of repair<br>• Safe and secure<br>• Adequately heated, fuel efficient and well insulated<br>• Contain up to date kitchens and bathrooms<br>• Well managed<br>• Located in attractive and safe environments<br>• Suit the specific requirements of the household (as far as possible) |

Whilst it could be argued that the additional categories, along with the proportional age of the stock, could explain the significant differences in the level of achievement between England and Wales, other explanations should be explored. As of 2009, 86% of public sector dwellings in England had achieved the

Decent Homes standard. For vulnerable dwellings in the private sector, 68% had achieved the Decent Homes standard by April 2006 (NAO, 2010). However, according to the Living in Wales survey undertaken in 2008, only 6% of public sector dwellings had achieved the WHQS in Wales (Welsh Government, 2012). It could be argued that one of the primary reasons for the delay in achieving the WHQS in Wales is due to the complexities surrounding the funding of the improvement measures required to meet the standard.

With the majority of public sector dwellings being owned and managed by local authorities at the time of these standards being implemented, there was an issue with funding the necessary improvements. Rules set by the Treasury mean that local authorities cannot borrow money against their dwelling assets (Baxter, 2008). In England, local authorities had a number of options to overcome this issue; they could either: retain full responsibility for their stock; enter into a Private Finance Initiative contract for the long-term design, build and management of local authority assets; set up Arms Length Management Organisations (ALMO's) to manage their stock; or transfer ownership and thus management to registered social landlords (RSLs) (NAO, 2006). With the ALMO option, the advantage is that the organisation could borrow against the dwellings whist local authorities retain ownership. However, the Welsh Government decided that the ALMO route was not a financially sound and viable option. Therefore, there were only two options available to local authorities in Wales; they could retain their stock or transfer their stock to a RSL (Baxter, 2008).

Accordingly, many of the local authorities in Wales went to ballot with their tenants for approval to transfer ownership to RSLs. However, it has taken many years for some local authorities to arrange the vote with their tenants and others were unsuccessful with gaining approval from the ballot (ibid). Where local authorities' stock has been retained or recently transferred, this has meant that many of the dwellings have remained not of a decent standard and thus goes some way to explain why the majority of public sector stock has not achieved the WHQS, as discussed above. Nevertheless, many local authorities were able to transfer their stock and are now making progress with achieving the WHQS, albeit not in the given timescale of by the end of 2012 (Baxter, 2008; Welsh Economy Research Unit, 2011).

Of particular significance for this doctoral research project, where the WHQS standard is achieved, the public sector dwellings in Wales could potentially have a higher level of energy efficiency than in England under the Decent Homes standard. The WHQS requires a minimum SAP rating of 65 to be achieved (HouseMark, 2008). Whereas the Decent Homes standard only stipulates specific energy efficiency measures, such as: that loft insulation is topped up where the existing thickness is 50mm or less; cavity wall insulation is installed, where appropriate; and energy efficient boilers are installed, where applicable (DCLG, 2006b). Whilst the results of the SAP and rdSAP methodologies are questionable, as discussed above, aiming to achieve a SAP rating of 65 will inevitably result in a more holistic and whole-house approach to improving the energy efficiency of public sector dwellings in Wales, when compared to the achievements of the Decent Homes standard in England. Although private sector dwellings in Wales are not covered by the WHQS, as they are under the Decent Homes standard in England, the Welsh Government's Arbed scheme provides a mechanism for addressing the energy efficiency of some of these additional properties.

### 2.3.4 Arbed

Arbed was set up by the Welsh Government in 2009 with the aim of improving the energy efficiency of the most deprived 15% of publically and privately owned existing dwellings in Wales. In recognition of the high levels of deprivation in Wales, European Structural Funds were invested by the Welsh Government to establish the Strategic Energy Performance Funding Programme to deliver localised economic, social and environmental benefits (Welsh Assembly Government, 2010c). From an economic perspective, Arbed aims to create opportunities for local employment and businesses that develop, install and maintain energy efficiency measures and renewable energy technologies.

The social benefits of Arbed are aimed at alleviating the impact of fuel poverty in Welsh homes and the environmental aspirations are that of contributing to Wales' target to reduce carbon emissions by 3% per annum. To maximise the benefits of Arbed, the objectives of the scheme are to: drive economies of scale by taking a whole-street and community approach; focus on communities with high levels of fuel poverty; take a whole-house approach to assessing required improvements; use local suppliers and installers wherever possible; and maximise utilisation of other funding mechanisms, such as the Carbon Emissions Reduction Target (Welsh Assembly Government, 2010d). Most significantly, Arbed funding can only be used to improve dwellings above the WHQS minimum SAP rating of 65 (Welsh Assembly Government, 2010b).

The first phase, which had the aim of being completed by March 31 2011, was implemented by housing associations and local authorities across Wales (Welsh Assembly Government, 2010c). These organisations were able to bid for a share of the £30 million funding by setting out a proposal, which included: the number of public and private dwellings to be improved; the Lower Super Output Area to which they resided; the types of measures to be installed; and how the objectives of the scheme would be met. The main energy efficiency measures implemented were: external wall insulation; connection to the mains gas network; solar thermal panels; solar photovoltaic panels; and heat pumps (Welsh Assembly Government, 2010b). As part of their proposal, housing associations and local authorities had to set out how they were going to evaluate the effectiveness of the interventions and thus demonstrate improvements in energy efficiency and reductions in carbon emissions (Welsh Assembly Government, 2010d). However, there was no guidance or methodology set out for these assessments.

As discussed above, the main method for assessing the energy performance of existing dwellings is using rdSAP and the accuracy of the results are questionable. Therefore the use of this method is unlikely to produce the aspired results for Arbed. Whilst the collection and analysis of empirical data is a funding criterion, without any other guidance or methodology, rdSAP is likely to be the dominant assessment method utilised to demonstrate improvements in energy efficiency. This could lead to misleading results and thus misrepresentation of meeting the objective of contributing to Wales' 3% annual reduction carbon emissions. However, whilst too late for phase one of Arbed, the rdSAP methodology has been enhanced to coincide with the launch of the UK Government's Green Deal initiative to improve the energy efficiency of existing dwellings.

### 2.3.4 Green Deal and Energy Company Obligation (ECO)

The Green Deal is a loan scheme designed to provide the upfront capital finance of up to £10k for energy efficiency improvements of buildings (AECB, 2011). The loan is attached to the building and not the owner or occupier, which is repaid through the energy supplier over a period of up to 25 years as a result of savings made on energy bills. When a home is sold or a new tenant moves in, the loan repayments pass onto to the new occupant. The ‘Golden Rule’ is that the money saved on energy bills should be equal or more than the loan repayments (DECC, 2010a). In addition, the repayment term should be no more than the life expectancy of the improvement measures that are installed (DECC, 2011a).

The golden rule is based on occupants heating their home to standard temperatures of 21°C in living rooms and 18°C in bedrooms during the heating season (AECB, 2011). As discussed above, these standard temperatures are used in rdSAP calculations. These rdSAP calculations form the basis for assessing eligibility for improvement measures installed through the Green Deal (Hirsch *et al*, 2011). However, the results of research by Hirsch *et al* (2011) has revealed that at least 80% of all UK households do not heat their homes up to these levels and thus only consume 70% of the energy required to achieve these standard temperatures. Furthermore, these results from Hirsch *et al* (2011) appear to be supported by another study undertaken by Deurinck *et al* (2011) in Flaunders. Using the Belgium equivalent to SAP, this study verified that the over estimation of pre-retrofit energy use due to the inaccurate baseline internal temperature, resulted in a significant difference in actual savings of 34% less than predicted. Consequently, these results indicate that inaccurate assessments and thus potential increases in energy bills could mean the criterion of the golden rule would not be met (Hiesch *et al*, 2011).

To overcome the issues of using a standard occupancy in rdSAP for Green Deal assessments, an enhanced version of the methodology is being developed whereby individual dwelling occupancies are taken into account (DECC, 2012). However, the author argues that it cannot be guaranteed that in the situation where a dwelling has new occupants that they will *'live'* in the same way as the previous occupants and thus use the same or similar quantities of energy. This scenario could lead to the new occupants having to pay more for their energy to cover the costs of the improvement measures. Furthermore, as argued in Hopper (2013), the potential limited knowledge and skills of a Green Deal Assessor, who are the only professional's authorised to undertake the enhanced rdSAP assessment for the purposes of utilising this initiative, could result in inappropriate improvement measures being installed. As discussed above, the specification of inappropriate materials and the use of inaccurate baseline data for assessments, could lead to savings that are less than those required to cover the costs of the repayments for the Green Deal loan.

There are two further scenarios where the golden rule is expected not to work; these are where: the household is on low income and therefore it is likely that energy use is already too low; and expensive improvements, such as solid wall insulation, are required and therefore repayments will not cover the capital cost within 25 years. For these circumstances, the Energy Company Obligation (ECO) has been developed to provide the additional finance required (DECC, 2011a). This additional finance is being provided by the six biggest energy companies in the UK, as a method of meeting their targets to reduce carbon emissions. As a result, it is anticipated that demand for these expensive improvement measures will greatly increase and thus drive down capital costs. However, there is concern that energy prices will increase to cover the costs of these expensive measures, which could have a significant negative impact on households who are already fuel poor and potentially push even more people into this category (AECB, 2011). Nevertheless, there are further significant challenges that need to be overcome in order to improve the energy efficiency of existing dwellings.

## 2.4 Challenges for improving the energy efficiency of existing dwellings

The challenges that exist for improving the energy efficiency of existing dwellings are vast and complex. First and foremost the challenges that surround addressing and understanding occupant behaviour in dwellings go far beyond the scope of this doctoral research project. However, the issues they present are nevertheless significant. Therefore, the fundamental issues are discussed in this section to provide the context for which occupant behaviour is relevant to this doctoral research project. This section then concludes with a further overview of the challenges that are encompassed by the technical solutions that exist when improving the energy efficiency of existing dwellings, specifically external wall fabric upgrades.

### 2.4.1 Occupant behaviour

One of the fundamental flaws with SAP and in particular, rdSAP (due to its relevance to existing dwellings and thus this doctoral research project) is that the methodologies are based on a standard occupancy. As discussed in Section 2.3.2 above, the standard occupancy assumes fixed internal temperatures and periods of time that these are reached, which are not a realistic reflection of occupant behaviour. Furthermore, it cannot be assumed that occupants will interact with their home in a ‘standard’ or predicted manner, which can have a significant impact on energy use and thus efficiency. For example, where occupants are not satisfied with having low-energy light bulbs, they will change these to more energy intensive alternatives that provide a better quality of light (National House Building Council, 2011). These claims are supported by Janda (2009), who argues that the differences in occupant behaviour can vary energy consumption by up to 300%; this was stated in the appropriately entitled paper “Buildings don’t use energy: People do”.

However, understanding occupant behaviour is claimed to be in its infancy and it is widely acknowledged that much more research is required due to the complexities and large variations that exist in the use of each and every home (Stevenson and Leaman, 2010; NHBC, 2011). Hence, the development and use of a standard occupancy in modelling tools, such as SAP and rdSAP, to overcome these issues (Deurinck *et al,* 2011). Nevertheless, much of the research on occupant behaviour that is being done is for new build dwellings using Post-Occupancy Evaluation techniques, which are discussed in more detail in Chapter Three. Following the results of some early studies, this type of research has seen an increase due to the number of dwellings that have not realised the designed performance of using less energy, for example through the adoption of the Code for Sustainable Homes (NHBC, 2011).

One of the significant and recurring results of research about occupant behaviour is that of the ‘rebound effect’ or ‘comfort take-back’. An example of this rebound effect is where savings in energy use for space heating purposes, as a result of improved levels of insulation, are not realised due to increased thermal comfort from higher internal temperatures or the purchasing of additional appliances and/or electrical equipment (Boardman, 2007; Herring and Roy, 2007; Hong *et al*, 2009; DECC, 2011b; Palmer and Cooper, 2011). The first example is particularly likely, and thus pertinent to this doctoral research project, where occupants are in fuel poverty as they are likely to have been living in homes with much lower internal temperatures to that of the standard occupancy levels (Boardman, 2007; Palmer and Cooper, 2011). This scenario is evidenced in the findings from the study by Hong *et al* (2009) where all case study dwellings that had received retrofitted insulation resulted in no reductions in energy use due to the rebound effect. All occupants were previously living in comfort conditions below the standard occupancy and were in fuel poverty. Furthermore, this meant that all occupants at these case study dwellings remained in fuel poverty despite the energy efficiency improvements. However, all occupants were now achieving adequate thermal comfort levels in their homes (ibid).

Another significant recurring finding is that occupants do not want to or have little to know understanding on how to use the controls of energy consuming systems and products within their dwelling (NHBC, 2011). It is further argued that whilst complex controls have the potential to achieve the maximum energy efficiency for heating and hot water systems, they are the least effective due to the lack of understanding on how to use them by occupants. However, automated systems, which are designed to overcome this issue, neither provide the desired energy efficiency improvements nor the level of comfort required by the occupants. Whilst the reasons are not fully explained by the NHBC (2011), it is indicated that it is due to the variations of occupant requirements whereby thermal comfort for one person is not necessarily the same for another.

At existing dwellings, the retrofit process presents an ideal opportunity to understand these variations in occupant behaviour, as well as encourage changes to reduce energy consumption (Institute for Sustainability, 2012). Unlike for new build, where it is only possible to undertake post-occupancy evaluations, dwellings receiving retrofitted improvement measures present an opportunity for interaction and data collection of occupant behaviour for before, during and after energy efficiency installations. In addition, involving occupants with decision making at the design, installation and implementation stages has the potential to achieve much greater awareness and thus changes in occupant behaviour to improve this crucial aspect of increasing energy efficiency in dwellings (ibid). However, whilst increasing awareness and encouraging changes in occupant behaviour appear to be fundamental in reducing energy use and subsequent carbon emissions *or* alleviating fuel poverty, these invariably need to be coupled with technical solutions, for example to improve the energy efficiency of heating and hot water systems and reduce heat loss through the fabric of dwellings, in particular.

### 2.4.2 Technical solutions

There are two main approaches to implementing technical solutions to improve the energy efficiency of existing dwellings; these are the measures-based approach and the whole-house approach. The former, which involves installation of individual measures, is the most common approach adopted, usually due to the limitations imposed by cost constraints and acceptable levels of disruption for occupants. In addition, the opportunities that arise as a result of being triggered by ‘other’ work that may be required within the dwelling, for example replacing an irreparable boiler, are usually more frequent and thus lead to individual improvement measures being installed. Whereas, the whole-house approach is mainly only undertaken where a major refurbishment project is being implemented (Construction Products Association, 2010).

The easy to install, relatively low-cost and thus common improvement measures installed in existing dwellings primarily consist of: cavity wall insulation; loft insulation; draught-proofing; hot water tank insulation; replacement windows and doors; replacement boilers; and low-energy lighting. More intrusive, costly and thus less common interventions include: solid wall insulation; ground floor insulation; mechanical ventilation with heat recovery; micro renewable energy technologies (Killip, 2008; Immendoerfer *et al*, 2008). Whilst all of these improvement measures are applicable to enhancing the energy efficiency of existing dwellings, this sub-section focuses upon external wall fabric upgrades due to their relevance to this doctoral research project.

### *Cavity wall insulation*

Whilst retrofitting cavity wall insulation is considered to be easy to install, there are a number of considerations that need to be taken into account. Retrofitting cavity wall insulation is claimed to only be suitable in dwellings that were built between the 1930's and 1980's, where the cavity is at least 50mm deep. Prior to the 1930's dwellings were usually constructed of solid exterior walls and thus do not have a cavity that can receive retrofitted insulation. In addition, many early cavity walls built during the 1920's have a depth of less than 50mm, which mean they are unsuitable for retrofitted cavity wall insulation. During the 1980's improvements in the building regulations introduced the installation of insulation in cavities during the construction of new dwellings. As a result, these post-1980 dwellings are invariably unsuitable for retrofitting additional cavity wall insulation (Immendoerfer *et al*, 2008; Construction Products Association, 2010).

To determine the suitability of cavity wall insulation to be retrospectively installed requires a survey to be undertaken by a suitably qualified professional in accordance with the National Insulation Association code of practice; this to check the depth of the cavity and that there is no debris or mortar obstructing the cavity. Where retrofitted cavity wall insulation is deemed suitable, it is injected into holes created in a specified pattern on the external leaf of the cavity wall. Once cavities are full, the holes are then filled and made good so that the holes can no longer be seen (ibid). The two most common insulation materials injected into existing cavity walls are mineral or glass wool and expanded polystyrene beads (Immendoerfer *et al*, 2008).

However, there are concerns about filling cavity walls with insulation retrospectively. Cavity walls were introduced to prevent moisture from being able to pass from outside to inside the dwelling, particularly in geographical locations that are classified as being at high risk of exposure to wind-driven rain. If moisture can ‘travel’ through the cavity, using the insulation as a means of passage, this can potentially lead to damp and mould growth on the internal surface of the external walls (Immendoerfer *et al*, 2008; Construction Products Association, 2010). Furthermore, if these cavity wall insulation materials get wet, the thermal performance is reduced (Stirling, 2001). Where cavity wall insulation is determined not to be suitable for retrofitting, it is recommended that these walls are treated as solid walls and thus upgraded with either internal or external wall insulation, which is discussed in the next section of this chapter. These are also the recommended methods for dwellings with existing cavity wall insulation and there is a requirement for these to be further improved. After all, the thickness and thus overall thermal performance of the insulation that can be retrofitted is determined by the depth of the cavity (BRE, 2003).

### *Solid wall insulation*

Solid walls can be insulated either internally or externally (EST, 2007). The decision of which to install is dependent upon a number of factors. As discussed above, along with in Section 2.2, solid wall construction was the primary method used to build dwellings up until the 1920's and therefore they are classified as hard to treat due to the lack of cavity to receive relatively easy to install thermal upgrades. The application of either internal or external wall insulation (EWI) changes the appearance of these traditional buildings, which is particularly significant where there is historic or aesthetic value attached (English Heritage, 2010b). Whilst these issues are considered in the Building Regulations, as discussed in Section 2.3.1, they are also likely to be subjected to requirements for planning permission, in particular for EWI applications (Boardman, 2007; Association for the Conservation of Energy, 2011).

Boardman (2007) argues that where a traditionally built dwelling has previously received an additional external layer, such as a waterproof render, the application of EWI is unlikely to be detrimental to their appearance. Therefore, planning permission is more likely to be granted. However, as discussed in Section 2.3.1 above, traditional solid walls are considered to be a breathable construction as they allow the absorption and evaporation of moisture through the fabric (May, 2005; English Heritage, 2010a; English Heritage, 2010b). If additional impervious layers, which includes EWI, are applied that do not maintain this breathability, there is a risk that the existing fabric and insulation will become damp and thus degrade, as well as reduce the thermal performance of the insulation (ibid).

Nevertheless, where traditionally built dwellings have previously received an impervious layer, such as a cement based render externally, removal may be more detrimental than retention (English Heritage, 2010b). Whilst there does not appear to be any literature to support this, it could therefore be argued that where dwellings have previously received an additional impervious layer, and there are no signs of deterioration, for example due to damp, the addition of solid wall insulation is unlikely to introduce any of these issues. However, this argument is in exception to thermal bridging. As discussed below, thermal bridging can have a significant impact on the overall thermal performance of external walls that have received retrofitted solid wall insulation.

In Section 2.3.1 it was discussed that the required U-Value to aim for when upgrading the thermal performance of solid walls is 0.30 W/m$^2$K (H. M. Government, 2010a). To achieve this reduction of heat loss, based on a standardised existing U-Value of 2.1 W/m$^2$K, predominantly results in the use of insulation materials with the lowest thermal conductivity (EST, 2006; Shore, 2008). As a result, the most common materials used externally are: Phenolic, Polyisocyanurate, Polyurethane and expanded Polystyrene foams; mineral wool; and cellular glass (EST, 2006). Nevertheless, most of these materials do not pose the permeability levels required to allow the existing wall to breathe as it was designed. As discussed in Section 2.3.1, materials such as mineral wool and cellular glass claim to have the vapour permeability properties required to maintain breathability. However, mineral wool and cellular glass do not have the necessary hygroscopic properties that it is argued are required for externally insulating solid walls (English Heritage, 2010a).

Conversely, English Heritage (2010b) states that virtually all insulation materials are suitable for use internally, regardless of their permeability and hygroscopic properties; this is due to claims that the breathability of layers closest to the inside are less critical than layers closest to the outside of solid walls. Therefore the breathability of outer layers of solid walls is paramount for ensuring that moisture can be evaporated externally and thus maintains the original designed energy performance. It is further argued by English Heritage (2010b) that the critical factor for internal wall insulation (IWI) is that there is a continuous vapour check layer incorporated on the warm side of the insulation. However, this vapour check layer must not be compromised, for example as a result of being punctured by the installation of fixtures and fittings, which is argued to be virtually impossible to achieve in reality.

Nevertheless, IWI is promoted as a viable option within the industry. The most common insulation materials discussed in literature for use internally include: plasterboard laminated with either Phenolic, Polyisocyanurate, expanded polystyrene or polyurethane foam, which are fixed directly to the existing internal surface of the external wall; and mineral fibre or wool fitted between battens that are either fixed directly to the existing internal surface of the external wall or with a gap to form a cavity behind the frame and insulation (EST, 2006; EST, 2008a; Immendoerfer *et al*, 2008). Despite this apparent promotion of IWI, EWI appears to have many advantages.

As discussed in Hopper *et al* (2011b), Hopper, (2012), Hopper *et al* (2012a) and Hopper *et al* (2012b), EWI has many advantages over IWI. The advantages include: increased opportunities to achieve a complete covering and thus remove risks posed by unavoidable thermal bridging, for example at partition wall and floor junctions; improved air tightness; thermal mass remains exposed to the internal space to aid control of overheating risks; less disruption to occupants; no loss of internal floor area; and internal fixtures and fittings do not have to be relocated or restricted to predetermined locations (Immendoerfer *et al*, 2008; Construction Products Association, 2010; English Heritage, 2010a; King and Weeks, 2010).

By wrapping the walls of a building in EWI, heat loss is reduced by sealing any gaps and cracks in the fabric that would otherwise cause draughts as a result of warm air being replaced by cold air. This cold air then requires heating, thus using more energy (EST, 2010a). The use of EWI can further reduce energy use as it allows the thermal mass of solid walls to be retained for use within the dwelling, which aids the maintenance of indoor comfort levels (Immendoerfer *et* al, 2008). However, the main advantage is the reduction of risks posed by avoidable thermal bridging, which cannot satisfactorily be overcome with internal wall insulation (Building Research Establishment, 2002; Immendoerfer et al, 2008). Nevertheless, achieving a complete covering of EWI at particular critical junctions to prevent all thermal bridging can be challenging. These junctions include: window and door openings, wall to roof junctions; window sills; and any projections, such as porches and conservatories (EST, 2006; Immendoerfer *et al*, 2008; Construction Products Association, 2010; English Heritage, 2010a).

Thermal bridging can lead to increased heat loss and thus a reduction in the overall thermal performance, along with internal surface condensation due to localised lower surface temperatures (Ward, 2006). The greater the level of insulation in buildings, the more significant thermal bridging becomes in terms of the overall thermal performance (Burberry, 1997). This is supported by claims that heat loss can be increased by as much as 30% as a result of thermal bridging between thermal elements and around openings (King and Weeks, 2010). However, the most serious effect of thermal bridging is claimed to be potential internal surface condensation as this poses a risk of damp and mould growth occurring, which could have severe consequences for the health of occupants (English Heritage, 2010a). Health issues associated with damp and mould growth includes: respiratory diseases; asthma; fungal infections; nausea and diarrhoea; and depression and anxiety (Roys *et al*, 2010). As discussed in Section 2.2 above, these types of health issues have a severe impact on society in terms of the wellbeing of occupants and subsequently the NHS.

Where thermal bridging does introduce internal surface condensation, to overcome this, occupants can either: increase the internal air temperature to raise the internal surface temperature above the dew point temperature of the air; or increase the rate of ventilation to reduce the dew point temperature of the air to below the dew point temperature of the internal surface. However, with either, or a combination of these approaches, energy use will be increased in order to maintain comfort levels (Burberry, 1997), which will undermine the overall effectiveness and thus purpose of the insulation. Furthermore, households in fuel poverty are unlikely to be able to afford to increase their energy use sufficiently to prevent the internal surface condensation and thus potential damp and mould growth occurring.

It can therefore be concluded that thermal bridging needs to be avoided wherever possible, in particular at dwellings where households are in fuel poverty. To prevent thermal bridging occurring, the method of implementing retrofitted solid wall insulation should involve individual preliminary surveys, which can then inform the production of appropriate technical detailing at the design stage of the retrofitting process, in particular for the critical junctions identified above (Energy Solutions, 2011). These design intentions then need to be executed on site, to ensure they are not undermined by poor workmanship (Immendoerfer *et al*, 2008; Thomsen and Rose, 2009). However, to determine if design intentions have been achieved, the collection and analysis of empirical data is fundamental. As demonstrated in Sections 2.2 and 2.3.1 above, the use of modelled data, based on a standard occupancy will not provide the accurate information required to fully assess the implications and results of retrofitting solid wall insulation to existing dwellings.

## Chapter summary

The purpose of this chapter was to set out the motivation for the research by critically reviewing literature that identified the gaps in knowledge during the early stages of the project. In doing this, the rationale for the research was underpinned by the acknowledgement and evidence that climate change, energy security and fuel poverty are directly linked to the energy efficiency of existing dwellings in the UK. With domestic buildings accounting for the largest proportion of carbon emissions and energy consumption in the UK, which have a direct impact on energy costs and thus fuel poverty, it has been demonstrated that improving their thermal performance is central to making a significant contribution to combating these issues. This was followed by an examination of the UK housing stock, in particular in England and Wales. This section demonstrated that there appears to be a direct correlation between the age and construction of existing dwellings and their theoretical overall thermal performance, which goes some way to explain the high levels of domestic carbon emissions, energy consumption and fuel poverty in the UK. Furthermore, Wales has a higher proportion of dwellings that were built before World War II.

This was followed by a review of some of the main policy drivers and strategies for improving the energy efficiency of existing dwellings in the UK: the Building Regulations; Energy Performance Certificates; the Decent Homes Standard for England and the Welsh Housing Quality Standard for Wales; Arbed; and the Green Deal and Energy Company Obligation. In this section it was demonstrated that the Building Regulations and Energy Performance Certificates have significant scope for driving the necessary improvements through these key pieces of legislation. However, it was revealed that there were a number of shortcomings, particularly for older traditionally built existing dwellings. Most notably, baselines, targets and assessments for improvements in thermal performance are founded on assumptions and models, rather than empirical data. In particular it was discussed that the adopted methodology for assessing existing dwellings, which is rdSAP, can lead to misleading results. In addition, there appears to be a lack of understanding and guidance for appropriate methods for improving the energy efficiency of traditional solid walls within these key pieces of legislation. Furthermore, rdSAP assessments undertaken for producing Energy Performance Certificates appear to fail to take account of variations in occupant behaviour.

Further significant drivers for improving the energy efficiency of existing dwellings in England and Wales that were discussed were the Decent Homes standard for England and the Welsh Housing Quality Standard for Wales. In this sub-section it was revealed that the Decent Homes standard in England appeared to have more scope as it targets all public and 70% of the most vulnerable private dwellings. This is in contrast to the Welsh Housing Quality Standard, which is only applicable to dwellings within the public sector in Wales. However, the

Welsh Housing Quality Standard requires a higher level of energy efficiency to be achieved than the Decent Homes standard, Therefore; it could be argued that the Welsh Housing Quality Standard will achieve greater improvements in energy efficiency than the Decent Homes standard. Nevertheless, England is more on target for achieving their standard within the given timescales than Wales due to the funding constraints imposed on Welsh public sector dwellings. Furthermore, the proportionally greater number of older dwellings in Wales could be directly correlated to the level of attainment of the Welsh Housing Quality Standard.

The two strategies for improving the energy efficiency in existing dwellings that were discussed were Arbed and the Green Deal, along with its Energy Company Obligation counterpart. It was demonstrated that the Arbed funding scheme appears to provide a means of addressing the gap for driving energy efficiency improvements in the most vulnerable privately owned dwellings in Wales, as well as those in the public sector, by targeting households that are in fuel poverty. However, there was a gap in the first phase of this initiative in the form of a lack of methodology for assessing the effectiveness of the energy efficiency improvements, which was a funding criterion of the scheme. As a result, it was discussed that the main method for undertaking the assessments that was likely to be adopted was the use of rdSAP and this is likely to lead to misleading findings. Any misleading findings could subsequently result in situations where it is claimed that a contribution has been made to the Welsh Government's target of a 3% reduction in carbon emissions, when in fact there is a possibility that this has not actually occurred.

The final strategy for improving the energy efficiency of existing dwellings that was discussed in this chapter was the UK Government's Green Deal loan scheme and Energy Company Obligation counterpart. For the Green Deal assessments of energy savings and thus repayments, it was discussed that there could potentially be issues if new occupants move into the dwelling, despite the proposed revisions to rdSAP calculations to include occupancy levels. It was further discussed that whilst the Energy Company Obligation will provide any additional funding required for low income households or for example where expensive solid wall insulation is required, there are concerns that this will increase energy costs across the board. In this scenario it is feared that this will put even more people into fuel poverty than it will alleviate.

The final section of this chapter discussed two of the main challenges that exist for improving the energy efficiency of existing dwellings: occupant behaviour and the technical solutions for upgrading external walls. Whilst a full review of literature that documents the challenges surrounding occupant behaviour were beyond the scope of this project, this section discussed the main issues that are relevant to this study. It was discussed that despite the shortcomings of SAP and rdSAP in particular, to take account of the large variations in occupant behaviour, through the use of a standard occupancy, these were the adopted methods for overcoming these issues. It was further discussed that many studies of occupant behaviour in domestic buildings were undertaken in new build dwellings using Post-Occupancy Evaluation techniques.

One of the most significant and repeated findings from studies of occupant behaviour was that of the rebound effect, whereby savings are absorbed by other uses of energy. This rebound effect was particularly important in a study that had been undertaken at existing dwellings that had received retrofitted energy efficiency improvement measures. The results from this study found that despite occupants having greater thermal comfort levels, they were still in fuel poverty due to the low levels of thermal comfort prior to the improvements. These findings could be particularly significant to the potential impact of carbon reductions claimed through the Welsh Government's Arbed scheme. A further issue that was discussed was that some occupants did not know or want to understand how to use the energy system controls in their dwelling. Finally, it was discussed that the retrofit process presents a unique opportunity to increase understanding and encourage changes in occupant behaviour, particularly where occupants are involved in the design, installation and implementation stages.

The retrofitting of cavity and solid wall insulation were the focus of the technical solutions to improve the thermal performance of external walls. It was discussed that whilst cavity wall insulation provides a low-cost and easy to install upgrade, it poses a risk of providing a passage for moisture into the internal surface of the external walls. Furthermore, not all cavities are suitable for retrofitting with insulation and the level of improvement it dictated by the depth of the cavity. Where cavity wall insulation is not deemed to be suitable or a greater level of thermal performance is required, it was discussed that cavity walls could be treated as solid walls. The two options for upgrading the thermal performance of solid walls are externally and internally applied insulation. The materials, methods of installation and issues for each were discussed. The most significant issues identified were maintaining breathability of solid walls and minimising avoidable thermal bridging.

It was discussed that whilst internal wall insulation appears to provide a suitable method of upgrading solid walls, particularly where there is historic or aesthetic value is attached to the external appearance of a dwelling, a strong argument was developed for using external wall insulation wherever possible. In addition, there were conflicting advisories from the very organisation that is responsible for providing guidance on upgrading the thermal performance of solid walls. English Heritage (2010a) states that maintaining the breathability of solid walls is paramount. Yet, English Heritage (2010b) states that any material was suitable to be used internally, regardless of its ability to maintain breathability. However, for externally applied insulation the advice from both documents is that breathability must be maintained. Nevertheless, the main arguments for using external wall insulation is that it improves air tightness, retains thermal mass on the inside of the dwelling and minimises opportunities for avoidable thermal bridging. These advantages are significant as they all assist with increasing thermal performance and minimising health issues, which can be associated with poorly installed upgrades.

Collectively, the sections in this chapter have set out a strong argument for the requirement to not only upgrade the thermal performance of existing dwellings but to also ensure that it is done in the appropriate way, which takes account of both the occupants and the fabric that is being improved. Furthermore, it has been clearly demonstrated that there is a strong argument for the collection and use of empirical data when evaluating the effectiveness of thermal upgrades to improve the accuracy of this information, as well as fill some of the gaps in existing knowledge.

# Chapter 3: Building Performance Evaluation: Existing Dwellings

# Chapter 3: Building Performance Evaluation: Existing Dwellings

As discussed in Hopper *et al* (2011b), the most common term for assessing and evaluating the thermal performance of new buildings is Post-Occupancy Evaluation (Leaman *et al*, 2010; Zimring, 2010). However, this type of assessment is also often referred to as Post-Construction Testing, Building Evaluation and Building Performance Evaluation (BPE). These terms are often used interchangeably and can also be used to describe studies that evaluate the performance of existing buildings (EST, 2005a; Gupta and Chandiwala, 2010; Leaman *et al*, 2010; TSB, 2010). For the purpose of this thesis, these assessments will be referred to as BPE hereafter. The rationale for this decision is that existing dwellings undergoing retrofitted energy efficiency improvement measures can often remain occupied for the duration of the works and therefore, in the opinion of the author, Post-Occupancy Evaluation does not seem appropriate.

Whilst BPE techniques are becoming more established for evaluating new dwellings, this chapter explores the potential for undertaking the assessments at existing dwellings. As a fundamental aspect of this research project, examining and thus understanding the methods and considerations for undertaking BPE is the main purpose of this chapter. Commencing by exploring the background and purpose of BPE in Section 3.1; this is followed by an examination of the main techniques used to collect and analyse data in Section 3.2. The chapter concludes with a review of some case studies that have implemented BPE techniques at existing dwellings in Section 3.3. As with the rationale behind BPE, reviewing case studies that have implemented some of the evaluation techniques offers an opportunity to learn from previous assessments that have been undertaken. Furthermore, the review of case studies offers an opportunity to further identify the gaps in knowledge that exist from similar research projects to this doctorate.

## 3.1 Background and purpose

Originating in the 1960's and 1970's, BPE assessments have evolved from individual case studies to evaluate the environmental performance of public and student dwellings, to more widespread use for public and commercial buildings by the mid 1980's (Stevenson and Leaman, 2010; Zimring, 2010). The main purpose of BPE is to obtain knowledge on: how a particular building is performing; how to make further improvements on future buildings; and occupant comfort levels and behaviour (Preiser, 2002; Leaman *et al*, 2010). As with product research, undertaking BPEs offers designers the opportunity to obtain feedback about changes in requirements, which can then be implemented in the development of future buildings and components (Preiser, 2002). For dwellings that are about to receive retrofitted improvement measures, undertaking BPE provides an opportunity to gather empirical baseline thermal performance and occupant comfort perception data; this can then be used to provide a comparison against thermal performance and occupant thermal comfort perceptions after installations are complete and further post-retrofit data is collected. However, these methods are an emerging area of research, which is in development and not well documented in literature (Gupta and Chandiwala, 2010).

As an output, publishing the results as case studies is an important aspect of BPE. If results are not shared, then it is more difficult for others to learn from the experience, which is one of the main objectives of BPE (Leaman *et al*, 2010).

However, to keep within the boundaries of the Data Protection Act 1998, all personal data must be anonymously documented and published, unless explicit permission is obtained from the building owner and occupier. A further desired output from BPE is obtaining a benchmark for energy use, based on occupancy, which does not exist for dwellings. One reason for this absence is due to the constraints posed by gaining access to collect the data (Stevenson and Leaman, 2010; Leaman *et al*, 2010). A potential additional reason is that the adopted method for assessing the thermal performance of existing dwellings is using the rdSAP modelling tool, which has a number of limitations, as discussed in Chapter Two above.

Benchmarks must be derived from empirical data, rather than theoretical or modelled data; comprising at least 30 studies in a given geographical area (ibid). This data can then be used to develop benchmarks for different dwelling typologies (detached, terraced, flat, etc) and occupancies (Leaman *et al*, 2010). However, for this data to be meaningful, it is not necessary to have 30 samples for each category, four of each is sufficient (Leaman *et al*, 2010; EST, 2008b). Once this data has been collected and analysed, a comparison can be made to establish an appropriate norm for different household types (Stevenson and Leaman, 2010). It is argued that the results of this type of BPE would be of particular relevance for demonstrating the effectiveness of retrofitted energy efficiency improvement measures at existing dwellings (NAO, 2008; Leaman *et al*, 2010).

## 3.2 Evaluation techniques

As discussed in Hopper *et al* (2011b), early BPE studies utilised questionnaires, interviews, site visits and field observations to gather information about buildings and their occupants (Zimring, 2010). These methods of data collection have evolved into established techniques, which in addition to those used initially, include: recording technical solutions and performance of the building fabric, services and systems; and assessing the environmental performance (Leaman *et al*, 2010; Lomas and Stevenson, 2010). It is claimed that the most challenging aspect of BPE is obtaining the cooperation of occupants in order to gain access, which often leads to low participant rates. This rationale also explains why BPE of dwellings is so underdeveloped (ibid). To try to overcome the issue of gaining occupant participation, the choice of methods should be limited, as far as possible, in terms of intrusiveness, duration and costs (Leaman *et al*, 2010).

Within the remit of BPE, is the potential to evaluate the thermal performance of dwellings that have received retrofitted energy efficiency improvement measures (NAO, 2008). However, to establish representative results, it is not always necessary to undertake all of the data collection recommended for new buildings (Leaman *et al*, 2010). This view is supported by early advocates of BPE. Zimring (1980) argues that adopted Post-Occupancy Evaluation methodologies should be based on the individual requirements of that particular study and thus the desired outcomes. For example, gaining an insight into occupant perceptions or establishing the performance of a particular building element, such as the heating system and controls. Nevertheless, it is argued by the TSB (2010) that where more than one building is being evaluated, there should be minimum common methods of data collection undertaken within a given study to ensure consistency and comparability between buildings.

This section focuses upon the techniques that have been developed and established for undertaking BPE and discusses some of the main data collection methods in turn. Whilst much of the discussions will be dominated by their use in new buildings, due to the infancy of their use at existing dwellings, the focus of each sub-section will aim to examine if and how the methods can be used in the domestic retrofit process. However, for many of the techniques, there is very little published guidance for use in dwellings and even less for retrofitted existing dwellings. The majority of the guidance that has been published is for use in non-domestic buildings.

Furthermore, the little guidance that does exist for monitoring and evaluating new build dwellings is predominantly targeted for instances where there is expected to be additional metering installed as standard, for example smart meters, which are not currently present in the majority of existing dwellings. Nevertheless, the techniques that will be discussed as thoroughly as possible are: occupant surveys; energy consumption monitoring; recording environmental conditions – internal and external; air-leakage pressurisation testing; thermographic surveys; in-situ U-Value measurements; co-heating tests; and field observations and photographic recording.

### 3.2.1 Occupant surveys

It is argued that occupant surveys are an appropriate method of verifying that a building is performing as expected from an occupant's perspective, along with providing additional information for assessments of energy efficiency, which can be undertaken using some of the techniques discussed in the other sub-sections below (3.2.2 to 3.2.8). As a result, occupant surveys can assist with explaining the reason for any discrepancies between design intentions and actual thermal performance (EST, 2009). These discrepancies can be explored through establishing an insight into the relationship that occupants have with their home and the impact that their actions have on thermal performance (Stevenson, 2010).

However, it must be borne in mind that there may be one or more variables that cause any discrepancies identified in the occupant surveys. Furthermore, these variables may be independent or interrelated and therefore the objective should be to make a generalisation of the potential causes, rather than make claims of definitive singular causes (Oppenheim, 1992). Yet it is argued by Leaman (2003) that even contradictory information provides useful data about the thermal performance of a building. After all it is the occupants that interact with the building and therefore *feel* any discomfort, caused for example by draughts, which an instrumental monitoring system may not be able to identify (ibid).

Additionally, Leaman (2003) argues that the most effective method for obtaining data from occupants about how they use a building is through the use of a short questionnaire. Whilst structured interviews, walk-through surveys and focus groups are also claimed to be effective methods of gathering useful data from occupants, it is argued that questionnaires provide the most robust method (ibid). However, questionnaires can be undertaken as structured interviews, either face-to-face or by telephone, as well as using the traditional self-administered and postal method (Oppenheim, 1992). There are, nevertheless, advantages and disadvantages of undertaking questionnaires using either the traditional postal method or as a structured interview.

The advantages of structured interviews compared to postal questionnaires are that they: generally result in increased response rates; offer an opportunity to clarify any misunderstandings or provide additional explanations where required; allow for participation of people with poor literacy; increase the opportunity for all questions to be answered and in the correct order; and ensure that the survey is completed by the participant for whom it is intended and therefore not passed onto someone else to be completed. The disadvantages include: increased costs and time requirements for undertaking the surveys; increased risks, which are associated with interviewer bias and influence; and potential difficultly and expense to reach a wide range of participants (ibid).

According to the TSB (no date), the content of questionnaires that form part of a BPE should aim to investigate: comfort; health; and control of the internal environment in relation to heating, cooling, lighting, noise and safety. Leaman (2003) claims that questionnaires should aim to collect information about users of a building that includes: comfort; health; satisfaction; demographic information, such as age, sex and time spent in the building; usability; and personal control. As part of the TSB's Retrofit for the Future projects, the EST (2009) states that questionnaires and interviews should include questions to determine: the number and age of occupants; thermal comfort perceptions; and level of energy consciousness amongst occupants.

Sheridan (2009), who discusses the methodological approach for POE of new dwellings, argues that information collected should include: heating system fuel and controls; use of appliances; number of occupants; household type; employment status; income details; occupants' preference for internal temperatures; and the use of heating, ventilation and appliances. Finally, in the home questionnaire developed by Hamilton (2002), questions about the following are included: number and age of occupants; opening of windows in winter and summer; presence of damp and mould growth on walls, ceilings, furniture, curtains and clothes; use of extract ventilation; and the type and quantity of energy consumed per annum.

### 3.2.2 Energy consumption monitoring

The EST (2008b) argues that the simplest and cheapest method of obtaining energy consumption data is to collect meter readings at the beginning and end of the monitoring period. This claim is also supported by English Heritage (2010b), who argues that collecting annual meter readings provides useful energy consumption data for existing dwellings, particularly where improvement measures are being installed. However, the EST (2008b) argues that more frequent readings should be taken, if possible. The EST (2008b) acknowledges that the robustness of this approach could be questionable as it will not be possible to detect if there are any mistakes in the data due to the infrequency that it is collected.

Nevertheless, the EST (2008b) recognises that the method of manually collecting meter readings from an occupied dwelling restricts the frequency that this can realistically be undertaken. The alternative is that this information is collected using an automated data logging system, which can either be collected manually, by connecting a laptop to the system or exchanging a memory card at regular predetermined intervals, or wirelessly. Nonetheless, the equipment required for these types of systems can be expensive to purchase, as discussed in sub-section 3.2.3 below. Furthermore, they require a continuous supply of power and the wireless systems also require a continuous connection to the internet (EST, 2008b).

To use this energy consumption data to compare one year's usage to another, it is argued that it needs to be *normalised* to account for variations in external weather conditions (H.M. Government, 2002; EST, 2008b). This comparison is particularly relevant for assessing the effectiveness of energy efficiency improvement measures (H.M. Government, 2002). As discussed in Section 2.1 above, space heating accounts for the largest proportion of domestic energy consumption, which is directly affected by external weather conditions. It is further argued that the simplest and most reliable method of analysing and thus normalising weather related energy consumption for comparison between two or more years is to use Heating Degree Days (H.M. Government, 2002; CIBSE, 2006).

Heating Degree Days are an expression of the average daily space heating requirements, based on the severity of the outdoor air temperature against an internal base temperature. In the UK, the assumed base temperature for all buildings, except hospitals, is given as 15.5°C (ibid). This means that for each day where the average outdoor air temperature is below 15.5°C it is assumed that space heating will be required. The base temperature is lower than the average internal temperature to allow for incidental gains, for example from occupants, lighting and electrical equipment (H.M. Government, 2002). Whilst it is recognised that every building is operated differently and thus likely to have different incidental gains and desired internal temperatures, as discussed in sub-sections 2.3.4 and 2.4.1 above, without the opportunity to collect actual internal temperatures this is argued to provide a good approximation for an average base temperature. However, these assumptions must be taken into account when using Heating Degree Days for weather related energy consumption (CIBSE, 2006).

The simplest method of calculating Heating Degree Days is to subtract the average daily temperature from the base temperature (ibid). For example, if the average daily temperature was 7°C, then the unit-less value given for the Heating Degree Day for that particular day would be 8.5 (15.5 – 7 = 8.5). On days where the average air temperature is above 15.5°C the Heating Degree Day value is given as zero (H.M. Government, 2002). These values can then be added together to provide weekly, monthly and annual number of Heating Degree Days. As a result, the higher the cumulated value, the colder the outdoor weather has been for any given period of time (CIBSE, 2006). However, it is not necessary to calculate Heating Degree Days in the UK as they are freely available to download from the internet. This data is published for 18 regions across the UK as monthly Heating Degree Days, which are based on the typical 15.5°C base temperature. There are also localised sources of this data available, which could be more appropriate to a particular building's location (H.M. Government, 2002; CIBSE, 2006).

### 3.2.3 Recording environmental conditions – Internal and External

Together with energy meter readings, as discussed in sub-section 3.2.2 above, internal and external air temperature readings are another basic and simple to implement method of monitoring for the purpose of undertaking BPE (EST, 2008b). Internal environmental conditions can also include relative humidity and carbon dioxide levels (TSB, 2010). As with energy consumption, this data can be collected manually or using an automated logging system. Manual readings can be collected with portable devices, with some able to collect all types of data using a single device. Automatic data logging systems can also incorporate all types of environmental data acquisition in a single device (EST, 2008b). For the latter, at least three sensors are recommended, with one placed in each of the main living room, master bedroom and the third close to the thermostat for the heating system (TSB, 2010). Whilst external environmental data can be obtained using the same methods as for internal data, it can also be collected by being downloaded from a local weather station via the internet (ibid).

Collectively, these data could provide a comprehensive representation of the environmental conditions and thus thermal comfort of the occupants, which ultimately impacts on energy consumption. However, the equipment and installation costs associated with collecting this data for internal environmental conditions can be significant. For example the TSB (2010) provide indicative costs of £2.5k per dwelling for automated data acquisition systems. As a result, costs of this level are likely to reduce the opportunities for these to be undertaken as part of retrofit projects, unless funding has been specifically allocated for this task. Projects that were part of the TSB’s Retrofit for the Future competition, which is discussed in Section 3.3 below, had funds allocated specifically for this and other monitoring equipment, as well the installation and evaluation of the outputted data.

### 3.2.4 Air-tightness testing

Unintentional air leakage and infiltration through cracks and gaps in the external envelope of a building can lead to increased energy consumption for space heating to achieve desired levels of thermal comfort (CIBSE, 2000; EST, 2005b; Knights and Potter, 2007). In recognition of this source of heat loss, the Building Regulations stipulate minimum levels of air-tightness for all new dwellings. Within Part L of the Building Regulations air-tightness is measured as the air permeability of the building fabric, which is defined as the rate of air leakage per hour per square metre at a differential of pressure of 50 Pascal (pa). The maximum allowable air leakage from new dwellings is 10 $m^3/h/m^2$ at 50 pa (H.M. Government, 2010b). However, as discussed in Sub-section 2.3.1 above, whilst improving air-tightness is a requirement for existing dwellings that are subject to requirements under Part L of the Building Regulations, there are no maximum levels of air leakage to be achieved and thus no testing is required. Nevertheless, the TSB (2010) stipulated air-tightness testing as a mandatory assessment for dwellings being improved through the Retrofit for the Future competition, which is discussed in more detail in Section 3.3 below.

The process of undertaking air-tightness tests is the same for both new and existing dwellings (EST, 2005a). The only difference between new and existing dwellings is that in the case of the latter where retrofitted energy efficiency improvement measures are to be installed, the test is usually undertaken twice; at least once both before and after the measures are installed. A comparison can then be made between the two tests as part of the assessment to determine how effective the improvement measures have been at increasing the energy efficiency of the dwelling (EST, 2005a; TSB, 2010). In preparation for and during the test: all internal doors must be left open; exterior doors, windows and adjustable ventilating openings, such as trickle vents, must be closed; and any combustion appliances and mechanical ventilation systems must be switched off (CIBSE, 2000; EST, 2005a; EST, 2005b). In addition, the test cannot be undertaken during wind speeds greater than three metres per second (m/s), according to CIBSE (2000) and six m/s according to Knights and Potter (2007) and the EST (2005b).

The procedure for undertaking the test involves using a fan, which is mounted in a temporary screen that is inserted into an external doorway, to move air into or out of the building to pressurise or depressurise the internal space, respectively (CIBSE, 2000; EST, 2005a; EST, 2005b). The air flow rate through the fan is then recorded at intervals of 10 pa, starting at 10 pa and finishing at 60 pa. The air permeability is then calculated by dividing the area of the building envelope by the flow rates recorded during the test (CIBSE, 2000; EST, 2005a; EST, 2005b; Knights and Potter, 2007).

Whilst Part L of the Building Regulations requires a maximum air permeability of 10 $m^3/h/m^2$ at 50 pa, the recommended good practice level is four $m^3/h/m^2$ at 50 pa for dwellings with whole house ventilation systems and seven $m^3/h/m^2$ at 50 pa for all other types of ventilation strategies. The best practice levels are three $m^3/h/m^2$ at 50 pa for both ventilation strategies (EST, 2005a). However, it is argued that air-tightness testing is limited in so far as the method only allows for the quantification of air leakage. The method does not allow for the identification of sources of air leakage, particularly where the designed levels of air permeability are not achieved. Therefore, it is recommended that visual methods of identifying the sources of air leakage are employed (CIBSE, 2000). The two methods recommended by CIBSE (2000) are the use of smoke generators, such as pencils, or thermography.

### 3.2.5 Thermographic surveys

As discussed in Hopper *et al* (2012b), all objects with a temperature above -273°C (absolute zero) emit radiant heat energy (EST, 2000; Pearson, 2002; EST, 2005a). Thermography is a technique for producing a visible image of this invisible heat energy (infrared radiation) emitted from the surface of an object, through a non-contact thermal imaging device, such as an infrared camera (Hart, 1991; Pearson, 2002; Snell and Spring, 2002; Infrared Training Center, 2010). This visual image is known as a thermogram, which is produced through the use of an infrared camera (Hart, 1991; Infrared Training Center, 2010). The thermogram is a map of the temperature difference across the surface of objects being viewed, which are displayed as different colours or shades of grey (Snell and Spring, 2002; Pearson and Seaman, 2003; Lo and Choi, 2004).

The EST (2000) argues that the most important aspect of thermographic surveys is interpreting the images. When interpreting thermograms it is necessary to understand the surface characteristics of the materials being viewed, in terms of their emissivity and reflectivity and vice versa (Lo and Choi, 2004). Only materials with a high emissivity provide a reliable reading. Materials with low emissivity will tend to reflect the temperature of surrounding objects and thus could produce misleading results, particularly where they are being interpreted by someone who has not undertaken appropriate thermography training (Snell and Spring, 2002; Lo and Choi, 2004; Infrared Training Center, 2010). Lo and Choi (2004) provide examples of emissivity and reflectivity values for some typical building materials. *“In general, non-metallic materials such as bricks and plaster have a high* *emissivity and metals (e.g. aluminium) have a low emissivity"* (Lo and Choi, 2004).

Whilst infrared thermography can be employed for undertaking both qualitative and quantitative surveys of buildings, Pearson (2002) argues that other methods should be adopted to quantify heat loss from a building as this requires the measurement of heat flow through the building element, such as a wall. In most instances qualitative thermographic building surveys provide sufficient information to identify anomalies through the identification of differences in surface temperatures. For example, to identify: continuity of insulation; occurrences and location of thermal bridges; occurrence and sources of air leakage, particularly at critical junctions; moisture and damp within an element; hidden components, such as pipes and wall ties; and electrical faults (Hart, 1991; EST, 2000; Pearson, 2002; Pearson and Seaman, 2003; EST, 2005a; Thomsen and Rose, 2009).

In particular, Pearson and Seaman (2003) argue that the use of infrared thermography is an efficient way of determining the effectiveness of insulation applied to the fabric of buildings. This claim is supported by Thomsen and Rose (2009), who have undertaken a study across Europe to analyse the occurrences and location of thermal bridges relating to execution quality on site, for both new build and retrofit building work. This is further supported by the EST (2000 and 2005a), where the use of thermography is advocated to assess the quality of workmanship for insulation installations, also for both new build and retrofit. The main advantage of using infrared thermography for undertaking these types of assessments to buildings, using either survey type, is that it is non-destructive. For example, to identify missing insulation and the location of thermal bridges would otherwise require intrusive investigations, such as the dismantling of construction elements (Snell and Spring, 2002).

When undertaking thermographic surveys of buildings, there are a number of criteria for the environmental conditions required to maximise the accuracy of the data being collected (Hart, 1991; Pearson, 2002; APT, 2011). However, there are discrepancies between some of the recommendations made. Hart (1991) recommends that the building surface should not be exposed to sufficient solar radiation that would affect results, during and for at least 12 hours prior to the survey. Hart (1991) continues by stating that cold and overcast days are the most suitable environmental conditions for undertaking thermographic surveys. Whereas, the EST (2000 and 2005a) argues that four hours should elapse following exposure to solar radiation prior to the survey and Pearson (2002) suggests that only one hour is required.

Pearson (2002) and the EST (2000 and 2005a) also recommend that surveys are undertaken in darkness to minimise effects from solar radiation. In Pearson's later publication (Pearson, 2011), the recommendations for undertaking surveys in the dark, as well as the addition of it being cold, cloudy, in the winter and no wind, are for external surveys only. For internal surveys, Pearson (2011) alludes that the criteria for environmental conditions are not significant. However, the BRE (2008) states that it is just more difficult to achieve the required environmental conditions for undertaking external surveys in the summer. Furthermore, the BRE (2008) explicitly states that internal surveys can be undertaken in the summer as long as the required temperature difference between the inside and outside of the building is achieved.

Nearly all recommendations are for a 10°C temperature difference between the inside and outside of the building at the time of the survey (Hart, 1991; EST, 2000; Pearson, 2002; Pearson, 2011). Hart (1991) and Pearson (2002) also state that this temperature difference should be achieved for the preceding 24 hours to the survey. However, the EST (2000) states that this 10°C temperature difference is only required for four hours prior to the survey. In addition, ADT (2011) recommend a temperature difference of just 5°C during and for the preceding four hours to the survey. The penultimate recommendation by all sources is that all surfaces must be dry at the time of the survey (Hart, 1991; EST, 2000; Pearson, 2002; EST, 2005a; ADT, 2011; Pearson, 2011). However, Pearson (2002) recommends that the building should not be exposed to any precipitation for the 24 hours prior to a survey. The final criterion is for wind speeds not exceeding: five m/s according to Pearson (2011); six m/s according to ADT (2011); 8 m/s according to the EST (2000 and 2005a); and 10 m/s according to Pearson (2002).

As discussed above, thermographic surveys can be undertaken from both inside and outside the building or a combination of the two (EST, 2000; Snell and Spring, 2002). Furthermore, given the restrictions imposed by the environmental criteria for undertaking these surveys, it is argued that there are greater opportunities to undertake internal surveys (Snell and Spring, 2002; Pearson, 2011). Nevertheless, external surveys provide a useful overall picture, particularly where a comparison is required to be made, either to another part of the same building or for before and after the installation of insulation (EST, 2000; EST, 2005a; Pearson, 2011; Hopper *et al*, 2012b). Pearson (2011) also argues that internal thermographic surveys can be undertaken to assess condensation risk, either calculated manually or using in-built features within modern cameras. Collectively, both internal and external thermographic surveys, along with assessing condensation risk, appear to be an effective method of collecting data from existing dwellings that are to receive, or have received retrofitted insulation.

### 3.2.6 In-situ U-Value measurements

To undertake conventional numerical u-value calculations, using software such as Build Desk, the exact layers and their dimensions of the construction that is used to build each thermal element needs to be known (Baker, 2011; Rye, 2011). In recognition of these facts, Historic Scotland appointed Baker (Baker, 2011), at the Centre for Research on Indoor Climate and Health at Glasgow Caledonian University, to investigate the effectiveness of these conventional calculations for use on traditional construction methods, such as solid walls. As part of this investigation, Baker (ibid) explored methods of measuring heat flow (u-values) in-situ. These methods were then employed on case study buildings and the results compared to conventional methods. The methods and further comparisons have also been employed by Rye (2011) on behalf of SPAB. Both sets of case studies have also included refurbished traditional buildings, which have received retrofitted insulation (Baker, 2011; Rye, 2011).

The resulting non-invasive method involves the use of a heat flux sensor, which is mounted to the internal surface of the external element, along with internal and external surface and air temperature sensors (Baker, 2008). The readings from each sensor are then recorded using a data logging system, at a maximum of 10 minute intervals over a period of at least one week within the winter months; this is to ensure a sufficient temperature difference between the internal and external environments (Baker, 2008; Rye, 2011). The u-value is then calculated using a prescribed formula and plotted against time (usually days) on a graph, which demonstrates the average heat flow during the monitoring period (ibid). The results of the case studies from both Baker (2011) and Rye's (2011) research projects demonstrate that in the majority of traditional wall constructions, heat loss is less than predicted through the use of conventional u-value calculation software. As discussed in sub-section 2.3.4 above, the incorrect use of baseline u-values at existing dwellings could lead to misleading expectations of improvements in energy efficiency following retrofitted insulation. Therefore, this technique appears to offer an opportunity to overcome the issue and provide a mechanism for providing these important baseline u-value data.

### 3.2.7 Co-heating tests

A further technique for acquiring baseline data for whole-house thermal performance and thus the performance of insulation in dwellings is co-heating tests (EST, 2008b; EST, 2009; TSB, 2010). The test is useful for identifying the actual thermal performance of dwellings that do not appear to be demonstrating the expected level of efficiency, for example as predicted in a SAP model. Thus, this test could be particularly useful for existing dwellings that are being retrofitted with insulation to improve their energy efficiency. Retrofitting insulation to existing dwellings can present many challenges to overcome, such as risks from thermal bridging and interstitial condensation, as discussed in Section 2.4.2 above, and therefore the predicted improvements in energy efficiency are not always realised (EST, 2009).

The process for undertaking a co-heating test involves heating the dwelling to maintain a constant internal temperature of at least 10°C above the external temperature throughout the duration of the test, which is usually between seven and 21 days (EST, 2008b; EST, 2009; TSB, 2010; Wingfield *et al*, 2010). As a result the test is usually undertaken in winter, although it is argued that the test can be performed at other times of the year provided the temperature difference is maintained (EST, 2008b; EST, 2009). However, it is necessary to minimise heating from solar gains and therefore this supports arguments for the test to be undertaken during the winter. Whilst solar gains can be accounted for and thus final calculations adjusted, it is argued that the accuracy of the results is reduced in these circumstances (EST, 2008b).

The dwelling is heated using electric resistance heaters. The energy input into the heater is measured and logged, together with the internal and external temperatures for the duration of the test. The heat loss coefficient (Watts per Kelvin) is then calculated by plotting the daily temperature difference between the inside and outside against the energy input required to the heat the internal space (TSB, 2010; Wingfield *et al*, 2010). A further and significant requirement is that for the duration of the test, the dwelling needs to be unoccupied and all electrical generating and consuming systems need to be switched off to avoid any external factors affecting the heat input and output (ibid). As a result, these requirements limit the opportunities to undertake a co-heating test, particularly in existing dwellings (EST, 2009).

### 3.2.8 Site visits, observations and photographic recording

As less frequently documented methods of collecting data, site visits, observations and photographic recording are usually undertaken at the same time as many of the other techniques described above in this section. The most common term used is walk-through surveys, where a photographic record is captured, particularly for retrofit projects whilst undertaking observations during site visits (EST, 2009; Leaman *et al*, 2010; Federal Facilities Council, 2001). The aim of the survey is to record any visible defects inside and outside the building. For retrofit projects, it is argued that the survey should be undertaken both before and after improvement measures are installed. During the post-retrofit survey, particular attention should be paid to any problem areas identified during the pre-retrofit survey, such as condensation or mould growth (EST, 2009).

## 3.3 Case study reviews: evaluations of existing dwellings

The purpose of this section is to review case studies that have undertaken BPE at existing dwellings where retrofitted energy efficiency improvement measures have been installed. Reviewing case studies offers an opportunity to examine the effectiveness of and thus any subsequent gaps in knowledge about the methods of data collection for undertaking BPE, as well as the effects of retrofitting energy efficiency improvement measures. Furthermore, these case studies provide an opportunity to explore some of the potential methods of setting out the approach for this type of research. This section concludes the critical review of published literature for this thesis by discussing the outputs of seven retrofit schemes.

The case studies are summarised in tables in each of the sub-sections below. However, the depth of discussion has also been dictated by the quantity of data that is available for each case study. Comprising different approaches to achieving the same goal of reducing energy use and carbon emissions from a range of geographical locations across the UK, the case studies examined are: (1) York Energy Demonstration Project; (2) Freedom from Fuel Poverty; (3) Royal Borough of Kensington and Chelsea; (4) Trefor Renovation Pilot Scheme; (5) Radian Housing Association; (6) Retrofit for the Future; and (7) Relish – Phase 1.

### 3.3.1 Case study 1: York Energy Demonstration Project

This case study is the product of monitoring undertaken by Bell and Lowe (1998 and 2000). The details about the case study project are set out in Table 5 below. This is followed by the results of the monitoring undertaken, which are set out in Tables 6 and 7.

**Table 5: Case study 1 project details**

| | |
|---|---|
| **Funding source** | The UK Government through The Greenhouse Programme |
| **Location** | Yorkshire |
| **Number of dwellings** | Stage one: four dwellings (focus of this case study review)<br>Stage two: 30 dwellings<br>Stage three: 200 dwellings |
| **Type of dwellings** | Two storey semi-detached and terraced, built with cavity walls and owned by the local authority |
| **Age of dwellings** | 1940's and 1950's |
| **Retrofit measures** | • Cavity wall insulation<br>• Loft insulation topped up to 200mm<br>• Low-emissivity double glazed windows<br>• Improvements in air-tightness where applicable<br>• Replacement heating and hot water systems necessary |
| **Monitoring techniques** | Short-term:<br>• Pre-retrofit and post-retrofit air-tightness testing<br>• Pre-retrofit and post-retrofit co-heating tests<br>• Post-retrofit thermographic surveys<br>Long-term monitoring (once the dwellings were re-occupied):<br>• Energy consumption<br>• Internal air temperature |
| **Additional information** | The four stage one dwellings were unoccupied during the retrofit process. Two dwellings (A & B hereafter) were connected to mains gas and two were not (C & D hereafter). For the long-term monitoring, data loggers were used to record the data over a period of 12 months once the dwellings were re-occupied. Energy meter readings were also collected to supplement the energy consumption data acquired using the data loggers. |

**Table 6: Results of short-term monitoring at Case study 1**

| Type of data | Case studies | | | |
|---|---|---|---|---|
| | A | B | C | D |
| **Air-tightness** (air changes per hour at 50 Pascal's) | | | | |
| Pre-retrofit | *Not tested*[4] | 19.3 | 16.9 | *Not tested* [5] |
| Post-retrofit | | 7.5 | 4.9 | 6.8 |
| Percentage improvement | | 61% | 71% | N/A |
| **Co-heating** (Watts per Kelvin) | | | | |
| Pre-retrofit (predicted[6]/ measured) | *Not tested* | 266/ 218 | 300/ 229 | *Not tested* |
| Post-retrofit (predicted/ measured) | | 149/ 133 | 132/ 121 | |
| Percentage improvement (predicted/ measured) | | 56/ 61% | 44/ 53% | |
| **Thermographic surveys**[7] | | | | |
| Post-retrofit only | Within the discussions that document the interpretations, it is argued that there was significant heat loss through the single glazed timber front doors at each of the dwellings. Furthermore, there appeared to be thermal bridging around each of the window and door openings. In case study D, missing or slumped insulation appeared to be evident below the ground floor front window. | | | |

[4] This dwelling was not tested due to the correct climate conditions not being available at the time when the tests were planned to be undertaken.
[5] As above, at the time of the pre-retrofit test the climate conditions were not suitable.
[6] The method used to calculate predicted heat loss coefficients were not disclosed in the case study publications, which restricts the ability to undertake a critique of the technique.
[7] Each thermographic image was accompanied by a visual photographic image to aid interpretation.

**Table 7: Results of long-term monitoring at Case study 1**

| Type of data | Case studies | | | |
|---|---|---|---|---|
| | **A** | **B** | **C** | **D** |
| **Energy consumption[8] (kWh) / carbon dioxide emissions (tonnes)** | | | | |
| Predicted pre-retrofit | 28,222 / 6.73 | | 24,805 / 12.64 | *No data* |
| Predicted post-retrofit | 14,166 / 3.8 | 14,805 / 3.8 | 12,028 / 7.4 | 9,889 / 5.3 |
| Actual post-retrofit | 14,369 / 3.12 | 13,059 / 2.97 | 12,225 / 6.23 | 12,296 / 6.27 |
| **Internal air temperatures (°C)** | | | | |
| Average | 17.3 | 16.9 | 19.6 | *No data* |

### 3.3.2 Case study 2: Freedom from Fuel Poverty

This case study is the product of monitoring undertaken by The Centre for Sustainable Energy (Banks and White, 2011). The details about the case study project and the dwellings are set out in Tables 8, 9 and 10. This is followed by the key findings from the monitoring, which are set out in Tables 11, 12, 13 and 14. Only key findings are set out due to the extensive discussion documenting the results. The majority of the monitoring was undertaken using qualitative methods of occupant questionnaires and interviews.

**Table 8: Case study 2 project details (part 1 of 2)**

| | |
|---|---|
| **Funding source** | Eaga Charitable Trust, managed by The Centre for Sustainable Energy |
| **Location** | Bath and North East Somerset |
| **Number and profile of dwellings** | 11 dwellings; private sector; mix of type and age (as set out in Table 10) |
| **Retrofit measures** | • Solid wall insulation (internal and external)<br>• Solar Hot Water (not monitored)<br>• Solar photovoltaic (not monitored) |

[8] Predicted energy usage was calculated using the National Home Energy Rating programme developed by the National Energy Foundation. As with the SAP modelling tool, the rating is based on a standard occupancy pattern, which on this occasion was two adults and two children whilst maintaining an indoor air temperature of 21°C in the living rooms for nine hours per day.

**Table 9: Case study 2 project details (part 2 of 2)**

| | |
|---|---|
| **Monitoring techniques** | • Pre-retrofit telephone survey (socio-demographic details)<br>• Pre-retrofit and two post-retrofit interviews (heating regime, methods of managing energy bills, and expectations and experiences of measures installed)<br>• Pre-retrofit and post-retrofit questionnaires (thermal comfort perceptions and difficulties with keeping warm and paying energy bills)<br>• Pre-retrofit energy consumption: modelled (SAP) and actual (from energy bills and meter readings)<br>• Post-retrofit energy consumption: modelled (SAP)<br>• Post-retrofit internal air temperatures<br>• Costs of measures<br>• Photographs before, during and after retrofit |
| **Additional information** | The aim of the study was to address the knowledge gap of the human barriers for the uptake of solid wall insulation using qualitative evaluation techniques. All households had to be in fuel poverty to be eligible to participate in the scheme. Full participation in the evaluations before, during and for 12 months after installations was also a condition of having the work undertaken at no cost to the occupants. |

**Table 10: Case study 2 dwelling and retrofit measure details**

| Case studies | Dwelling type | Heating energy fuel | Retrofit measure |
|---|---|---|---|
| **1** | Park Home | Electric | EWI |
| **2** | Park Home | Oil | EWI |
| **3** | 1950's Semi | Mains Gas | IWI |
| **4** | Mendip stone, mid-terrace | Mains Gas | EWI (rear only) |
| **5** | 1930's Semi | Calor Gas | EWI |
| **6** | 1930's Detached bungalow | Mains Gas | EWI and PV |
| **7** | Mendip stone, end-terrace | Oil | IWI and PV |
| **8, 9 and 10** | 1940's Steel frame, Semi | Mains Gas | EWI |
| **11** | 'Cornish House', Semi | Mains Gas | EWI |

**Table 11: Pre-retrofit findings from Case study 2: Methods of managing energy bills**

| Methods of managing energy bills | Number of dwellings |
|---|---|
| Turned heating off, though preferred to have it on | 2 |
| Turned the heating down, though preferred to have it warmer | 5 |
| Turned the heating down or off in some rooms but not others | 5 |
| Only heated and used one room for periods of the day | 3 |
| Used less hot water than would have preferred | 3 |

**Table 12: Pre-retrofit and post-retrofit findings from Case study 2: Thermal comfort perceptions and energy consumption**

| Pre-retrofit | Post-retrofit |
|---|---|
| **Thermal comfort perceptions** (Number of dwellings) | |
| Much colder than would have liked (5)<br>A bit colder than would have liked (5)<br>About right (1) | A bit colder than would have liked (1)<br>About right (9)<br>*(Note: result of one dwelling is not documented)* |
| **Energy consumption**[9] | |
| Large variations between modelled and actual consumption. In nine of the 11 dwellings, actual consumption was less than modelled. However, for one of the dwellings the two figures appear to be very close. For the other two dwellings, actual consumption was higher than modelled. | In six of the 11 dwellings the modelled consumption after retrofit was more than the actual consumption before. However, for one dwelling the two figures appear to be very close (this is a different dwelling to that which had figures close before retrofit). For the other five dwellings, the modelled consumption after retrofit was lower than the actual consumption before retrofit. |

**Table 13: Post-retrofit findings from Case study 2: Internal air temperatures**

| **Internal air temperature**[10] |
|---|
| Daily average temperatures were compared to the standard occupancy level of 21°C. Six dwellings were on average below the standard. Four of the dwellings were on average at the standard. One dwelling was on average above the standard. |

**Table 14: Further findings for Case study 2: Cost of measures and photographs**

| **Cost of measures** |
|---|
| The average cost for the insulation works was £8,501, which represented 54% of the total costs. Survey and design work represented 31% and additional works[11] represented 15% of the total costs. The Average total cost per dwelling was £15,746. |
| **Photographs** |
| Photographs before, during and after retrofit for only one dwelling are shown within the report. Furthermore, only one photograph at each stage is included, which shows the whole front facade. |

[9] Results are displayed on a graph without any accompanying raw data.
[10] Results are displayed on a graph, which appear to be sourced directly from the data loggers.
[11] The report does not document what the additional works entailed.

### 3.3.3 Case study 3: Royal Borough of Kensington and Chelsea

This case study is the product of an investigation undertaken by Energy Solutions (2011). The details about the study are set out in Tables 15 and 16, followed by descriptions of the dwellings in Tables 17 and 18, and the findings from the study in Tables 19, 20 and 21 below.

**Table 15: Case study 3 project details (part 1 of 2)**

| | |
|---|---|
| **Location** | Royal Borough of Kensington and Chelsea, London |
| **Number and profile of dwellings** | Five dwellings; private sector; solid wall construction; mix of type (details set out in Tables 17 and 18) |
| **Retrofit measures** | Variety of measures according to property (as set out in Tables 19 and 20) |
| **Monitoring techniques** | • Post-retrofit u-value measurements of thermal elements that were improved, based on SAP<br>• Costs of improvement measures<br>• Pre-retrofit and post-retrofit SAP analysis to ascertain:<br>○ Overall rating (0-100)<br>○ Annual energy cost savings<br>○ Annual carbon emission savings |
| **Additional information** | The aim of the study was to explore cost effective retrofit solutions for hard to treat solid walled dwellings. Each dwelling had a maximum budget of £7000 that could be spent on a package of retrofit solutions to reduce energy consumption and carbon emissions. |

**Table 16: Pre-retrofit details of Case study 2 dwellings (part 1 of 2)**

| Case study | Type description | Details |
|---|---|---|
| **A** | One bedroom ground floor flat within mansion block in a corner location. | Solid brick walls (343mm thick).<br>Part suspended timber and part solid ground floor.<br>Portable electric heaters.<br>Single glazed timber windows and solid timber doors. |
| **B** | One bedroom first floor Victorian terrace flat, situated above a commercial property. | Solid brick walls (225mm thick).<br>Gas combination boiler.<br>Single glazed timber windows and solid timber doors. |

**Table 17: Pre-retrofit details of Case study 2 dwellings (part 2 of 2)**

| | | |
|---|---|---|
| **C** | One bedroom first floor Victorian terrace flat situated above a commercial property. | Solid brick walls (225mm thick).<br>Electric storage heaters.<br>Single glazed timber windows and roof light and solid timber doors. |
| **D** | Converted basement flat in three storey mansion house. | Solid brick walls (225mm thick) with IWI (U-value: 0.30 W/m²K).<br>Suspended timber floor with insulation (U-value: 0.25 W/m²K).<br>A rated Gas combination boiler with programmer, room thermostat and TRVs.<br>All except one window was double glazed UPVC (u-value: 2.0 W/m²K). The other was single glazed with timber frame.<br>Solid timber doors. |
| **E** | Three storey end terrace house. | Solid brick walls (225mm thick).<br>A rated Gas condensing combination boiler with programmer, room thermostat and TRVs.<br>Mix of double glazed UPVC and single glazed timber windows and solid timber doors. |

**Table 18: Details and costs of retrofit measures for Case study 2 (part 1 of 2)**

| Case study | Retrofit measures | (post-retrofit U-value) | Cost (£) |
|---|---|---|---|
| **A** | New gas boiler, controls and radiators | | 6000 |
| | Draught proofing | | 500 |
| | Low energy lights | | 30 |
| | | *Total* | 6530 |
| **B** | Replacement flat roof with insulation | (0.18 W/m²K) | *No data* |
| | Dry lining (IWI) in living room and bedroom | (0.34 W/m²K) | 2177 |
| | Secondary glazing | | *No data* |
| | Draught proofing | | 500 |
| | Low energy lights | | 30 |
| | Heating controls pack | | 350 |
| | | *Total* | 3057 |
| **C** | Replacement flat roof with insulation | (0.18 W/m²K) | 3000 |
| | Dry lining (IW) in living room and bedroom | (0.34 W/m²K) | 2083 |
| | Secondary glazing | | 1325 |
| | Draught proofing | | 500 |
| | Low energy lights | | 30 |

| | | |
|---|---|---|
| | *Total* | 6938 |

**Table 19: Details and costs of retrofit measures for Case study 2 (part 2 of 2)**

| | | |
|---|---|---|
| **D** | Improved wall insulation (IWI) (0.25 W/m²K) | 500 |
| | Improved ground floor insulation (0.18 W/m²K) | 340 |
| | Replacement window (1.6 W/m²K) | 300 |
| | Flue Gas Heat Recovery device | 55 |
| | Waste Water Heat Recovery device | 700 |
| | Draught proofing | 350 |
| | *Total* | 2245 |
| **E** | EWI on gable wall (0.25 W/m²K) | 5400 |
| | Draught proofing | 500 |
| | Low energy lights | 55 |
| | *Total* | 5955 |

**Table 20: Results of estimated thermal performance improvements at Case study 3**

| Case study | Pre-retrofit SAP rating | Post-retrofit SAP rating | Carbon emissions reduction (kg/year) | Energy costs reduction (£/year) |
|---|---|---|---|---|
| **A** | 10 | 47 | 3312 | 786 |
| **B** | 11 | 41 | 2974 | 659 |
| **C** | 11 | 41 | 2974 | ~659 |
| **D** | 79 | 81 | 180 | ~29 |
| **E** | 31 | 41 | 1162 | ~189 |

### 3.3.4 Case study 4: Trefor Renovation Pilot Scheme

This case study is the product of a pilot scheme undertaken by Cymdeithas Tai Eryri, which has been produced by Horan (2011). The details about the study are set out in Table 22, followed by the findings, which are set out in Tables 23, 24, 25 and 26 below.

**Table 21: Case study 4 project details**

| | |
|---|---|
| **Location** | Trem y Môr, Trefor, Gwynedd, North Wales |
| **Number of dwellings** | Five dwellings |
| **Type of dwellings** | Terraced, built with solid walls and owned by Cymdeithas Tai Eryri (social landlord) |
| **Age of dwellings** | Pre-1930's |
| **Retrofit measures** | • Roof insulation (at pitch level to create a warm roof within the original house and at ceiling level in the single storey kitchen extensions)<br>• New windows and doors<br>• External wall insulation (at the rear)<br>• Internal wall insulation (at the front)<br>• Solar hot water panels<br>• Air-source heat pumps (at four dwellings)<br>• Biomass boiler (at one dwelling) |
| **Monitoring techniques** | • Pre-retrofit condition survey to assess most appropriate improvement measures (undertaken by the BRE)<br>• SAP assessments to produce EPC certificates<br>• Pre-retrofit and post-retrofit energy consumption and carbon emissions (based on complete or part annual meter readings and delivery invoices for coal or oil)<br>• Post-retrofit occupant questionnaires (one immediately after retrofit and a second 12 months after retrofit)<br>• Costs of measures |
| **Additional information** | The aim of the pilot study was for the social landlord to establish methods of improving the thermal performance of its stock, particularly those that are not on mains gas, as part of undertaking work required through the Welsh Housing Quality Standard. |

**Table 22: Case study 4 dwelling details**

| Type of data | Case studies | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| Floor area ($m^2$) | 80 | 73 | 102 | 51 | 65 |
| Number of bedrooms | 3 | 3 | 3 | 2 | 2 |
| Number of occupants | 5 | 4 | 3 | 4 | 3 |

**Table 23: Pre-retrofit findings for Case study 4 dwellings**

| Type of data | Case studies | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| Annual electricity (kWh) | 8859 | 11552 | 7713 | 5898 | 5683 |
| Annual coal (kg) / oil (ltr) | 3000 kg | 1500 kg | 1500 kg | 2400 ltr | 3000 kg |
| Annual energy costs (£) | 1903 | 1686 | 1346 | 1683 | 1508 |
| Annual carbon emissions (kg) | 11813 | 9226 | 7687 | 9784 | 10026 |
| SAP rating | 32 | 40 | 17 | 64 | 39 |

**Table 24: Costs of retrofit measures for each dwelling within Case study 4**

| Retrofit measures | Case studies | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| IWI (front external walls) | £2365 each | | | | |
| EWI (rear external walls) | £3003 | £3003 | £3003 | £2073 | £3003 |
| Warm roof insulation | £3075 | £3416 | £3075 | £3075 | £3075 |
| Cold roof insulation | £132 | - | £561 | - | £220 |
| Biomass boiler and 7 radiators | £7200 | - | - | - | - |
| Air source heat pump and 7 radiators | - | £7200 each | | | |
| Solar thermal panel system with cylinder | £4650 each | | | | |
| *Total* | £20425 | £20634 | £20854 | £19363 | £20513 |

**Table 25: Post-retrofit findings for Case study 4 dwellings**

| Type of data | Case studies | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| Annual electricity (kWh) | 5262 | 5700 | 9351 | 9628 | 6553 |
| Annual energy costs (£) | 720* | 713 | 1285 | 1087 | 898 |
| Annual carbon emissions (kg) | 2869* | 3108 | 5098 | 5249 | 3573 |
| SAP rating | 65 | 69 | 40 | 67 | 68 |
| SAP rating improvement | 33 | 29 | 23 | 3 | 29 |

* These figures do not include the wood fuel for the biomass boiler as the occupants receive it free from a family member.

## Chapter summary

The purpose of this chapter was to: explore the background and rationale for undertaking BPE assessments; to examine the methods and techniques used to collect and analyse the data; and to review a small selection of existing case studies where BPE has been undertaken at existing dwellings. BPE has evolved since the 1960's into an important aspect of the building construction process to enable the lessons learnt from previous experiences to be implemented within future creations. In addition, pre-retrofit data collection was identified as a prerequisite within the emerging field of undertaking BPE for existing buildings. This pre-retrofit data provides a baseline for assessing the improved energy performance against at the post-retrofit stage. However, it was discussed that a lack of benchmark for domestic energy use, based on occupancy, demonstrates the lack of BPE activity that is undertaken at existing dwellings in the UK, despite the established methods and techniques that are available.

The methods and techniques examined included: occupant surveys; energy consumption monitoring; recording external and internal environmental conditions; air-leakage pressurisation testing; thermographic surveys; in-situ u-value measurements; and site visits, observations and photographic recording. For each of these techniques, the focus was on the method of use for assessing existing dwellings, as much as possible, as well as the advantages and disadvantages. However, the limitations of this were recognised due the lack of experience documented in the literature. This was further emphasised in the review of the case studies. Whilst it is recognised that the review was not exhaustive, it did provide an overview of the types of case studies that exist in the literature. The four case studies were from different geographic locations (north

England, south east England, south west England and Wales). Whilst each case study provides valuable data, not one was based entirely on empirical data. The first case study was the closest to just using empirical data. However, this did not include baseline energy consumption data. Collectively, this chapter has provided a valuable link between the literature review to set out the motivation for this doctoral research project in Chapter Two and the methodology adopted to collect and analyse the data, which is set out Chapter Four and based on the methods and techniques discussed in this chapter.

# Chapter 4: Methodology

# Chapter 4: Methodology

In making a significant and original contribution to knowledge, the purpose of this doctoral research project is to investigate the impact of retrofitted external wall insulation (EWI) on the thermal performance of existing dwellings in Swansea. The retrofitted EWI was procured by two housing associations, based in Swansea, as part of the first phase of the Welsh Government's Arbed scheme. The Arbed scheme was instigated on the basis that existing dwellings in Wales with the poorest thermal performance make a significant contribution to high levels of domestic energy consumption and thus carbon emissions, which have a direct impact on climate change, energy security and fuel poverty. The Welsh Government has set a target to reduce carbon emissions by 3% per annum from 2011; this should assist with Wales making a contribution to the UK's legally binding target of reducing carbon emissions by 34% by 2020 and 80% by 2050, based on 1990 levels. One of the main objectives of the Arbed scheme is that the energy efficiency improvements should make a contribution to meeting these carbon emission reduction targets.

Additionally, the relationship between the poorest thermal performance and the age and construction type of existing dwellings appears to be significant. With over 33% of existing dwellings in Wales having been built before 1919 with solid exterior walls, together with the portrayal that these are the least energy efficient, there is an urgent impetus to improve the thermal performance of these dwelling types. One of the main methods of improving the thermal performance of solid exterior walls is retrofitting EWI. Retrofitting EWI is also expected to be one the main interventions implemented through the UK Government's Green Deal finance initiative, which is available in Wales. This initiative provides up to

£10,000 per dwelling on a loan basis, which is repaid through energy bills. Repayments should be equal or less than the savings that have resulted from the energy efficiency improvements and completed within the life expectancy of the intervention. However, the method of assessing levels of improvement in energy efficiency for the loan repayments is through the use of modelled calculations using theoretical data, rather than through the use of empirical data. Modelled calculations are also the predominant method of assessing thermal improvements for the Arbed scheme. Chiefly, the modelling tool used for these calculations at existing dwellings is rdSAP, which has a number of deficiencies.

The two main deficiencies that have been identified are the use of an assumed u-value of 2.1 W/m$^2$K for heat loss though solid walls and a standard occupancy space heating pattern. One of the dangers of using an assumed u-value is that if the solid wall has a superior thermal performance than predicted through modelling, there will be greater reductions in heat loss expected than will actually be achieved with the level of insulation installed. Furthermore, to achieve maximum thermal performance it is necessary that there is continuity of the insulation and thus thermal bridging is avoided wherever possible, which can have a significant impact of the overall improvement.

The main issue with using a standard occupancy is that it is unrealistic as it does not represent typical occupant behaviour. No two homes will be heated to the same internal temperature and for the same amount of time each day and week. There is also the issue of comfort take back or the rebound effect, particularly in dwellings where the occupants are in fuel poverty. In this situation potential savings created by energy efficiency improvement measures are completely or partially absorbed by occupants increasing their thermal comfort levels. However, whilst carbon emissions may not be reduced, the evidence suggests that there may be reduced demand on the NHS as a result of improved comfort and thus living conditions.

Finally, in addition to the lack of methodology for meeting the Arbed I funding criterion of assessing the effectiveness of the retrofitted EWI, the motivation of this doctoral research project is centred on making a contribution to filling gaps in knowledge about improving the energy efficiency of existing dwellings, as summarised in this chapter thus far. Collectively, these gaps in knowledge are focussed upon the identification that very little monitoring and evaluation is undertaken at domestic buildings and thus more knowledge is required about the thermal performance of existing dwellings, which has resulted in a lack of published:

- Baseline energy performance data for existing dwellings based on empirical data (and not modelled data), which allows for an accurate assessment of improvements following retrofitted energy efficiency measures;
- Data about the effects of occupant behaviour in respect of energy consumption, in particular comfort take back (rebound effect), which is based on empirical evidence;
- Retrofit case studies that have undertaken cost assessments based on empirical data (and not modelled data) from schemes that have similar budgets to the Green Deal;
- Retrofit case studies that document what can go wrong on site, before and during installations; and

- Methodologies for obtaining empirical data about the construction quality and energy performance of dwellings that have received retrofitted EWI, which can be implemented at low cost and not use theoretical modelling tools, such as SAP or rdSAP;

As a result of identifying these gaps in knowledge, the aim and objectives of this doctoral research project are (recapped) as follows:

### *Aim*

To investigate the link between the construction quality of retrofitted external wall insulation and the resulting impact on energy efficiency for existing dwellings in Swansea.

### *Objectives*

1. To appraise the implementation and execution of retrofitted external wall insulation at the Arbed I case study dwellings, to determine the effects on the quality of the installations.
2. To determine the value of and the need for non-invasive investigation techniques to confirm the construction quality and thermal integrity of retrofitted external wall insulation.
3. To assess the energy and carbon emission reductions together with the cost effectiveness of retrofitting external wall insulation at the Arbed I case study dwellings and identify any relationship to post-retrofit occupant thermal comfort perceptions and behaviour.
4. To determine the value of and need for empirical energy consumption data to confirm the energy performance of traditional dwellings that have received retrofitted external wall insulation.

To meet these aim and objectives, the research problem has been defined as an overarching research question, which has been subsequently broken down into sub-questions as set out in Section 4.1. This is followed by the research approach that has been adopted to answer the research questions in Section 4.2. To conclude, Section 4.3 discusses the research methods, which sets out how the data was collected and analysed to answer the research questions and thus meet the aim and objectives of this doctoral research project.

## 4.1 Research questions

To define the research problem, an overarching research question evolved. This research question is founded on the scope and limitations of the contribution that this research project can make to filling the gaps in knowledge, which are relevant to retrofitting EWI at existing dwellings in Swansea through the first phase of the Welsh Government’s Arbed scheme. This overarching research question has been divided into sub-questions, which in turn have been broken down into further detailed questions to ensure the approach and methods are focused and thus effective at meeting the aim and objectives of this doctoral research project. This section sets out each of these questions in turn, along with the rationale to demonstrate the justification and purpose for including each of the questions.

### *Overarching research question*

**How effective was the retrofitted external wall insulation, in terms of quality and impact on energy efficiency at the Arbed I case study dwellings in Swansea?**

The rationale for this overarching research question is that it encompasses the doctoral research project as a whole; whilst at the same time provide enough detail to specifically explain the context of what is being set out to be achieved from the data collection and analysis.

***Sub-question 1***

*What can be learnt from the implementation and execution of the retrofitted EWI at the Arbed I case study dwellings, which can be carried forward to improve future installations through other activities, such as the Green Deal?*

- *a Did the technical solutions implemented have an effect on the quality of the installations?*
- *b Did the method of execution have an effect on the quality of the installations?*
- *c Did the quality of the installations have an effect on the reductions of visible heat loss?*
- *d Do any of the lessons learnt have any implications for other initiatives, such as the Green Deal?*

The rationale for this sub-question is that it addresses the effects of construction quality on the resulting energy efficiency improvements, which is missing from existing literature. By focussing upon the implementation and execution of retrofitting EWI and linking the findings to actual energy consumption, the answer to these detailed questions addresses the objectives of this doctoral research project. Furthermore, it is anticipated that the answers to these questions will provide valuable empirical evidence that can be taken into account during future retrofit schemes.

### Sub-question 2

*Has the retrofitted EWI resulted in reduced energy consumption and thus carbon emissions at the Arbed I case study dwellings?*

- *a What are the actual annual energy use and carbon emissions, per square metre of floor area, before and after the EWI was installed?*
- *b Has the retrofitted EWI contributed to the Welsh Government's target of reducing carbon emissions by 3% per annum?*

This sub-question is central to this doctoral research project in that the answer will provide empirical data about pre-retrofit and post-retrofit energy consumption and carbon emissions that is missing from the majority of published case studies, which document the results of evaluations of retrofitted existing dwellings. Furthermore, the answers of the detailed questions will contribute to meeting objectives two, three and four to determine: the cost-effectiveness of the retrofitted external wall insulation; any relationship between occupant thermal comfort and behaviour with energy efficiency improvements; and whether retrofitting external wall insulation can realise energy consumption and carbon emission savings, which will contribute to the Welsh Government's annual target.

### Sub-question 3

*Is retrofitting EWI cost effective?*

- *a How much did the EWI installations cost per dwelling?*
- *b Do the energy savings over the life expectancy of EWI cover the capital costs, based on available energy prices?*

The rationale for this sub-question is that the answer will provide empirical data about the cost-effectiveness of retrofitting EWI, rather than modelled data from theoretical calculations. Linked to objectives two and three, the answers to these detailed questions are central to demonstrating the viability of retrofitting EWI through the UK Government's Green Deal initiative.

### *Sub-question 4*

*Are occupant thermal comfort perceptions and behaviour consistent with energy consumption and cost-effectiveness results at the Arbed I case study dwellings?*

- *a Have the occupant's perceptions of their thermal comfort changed since the retrofitted EWI was installed?*
- *b How do occupants behave towards energy consumption since the retrofitted EWI was installed?*
- *c How do occupant thermal comfort perceptions correlate with energy consumption and costs?*

The rationale for this sub-question is to identify any potential relationships between before and after energy consumption with occupant thermal comfort perceptions and their behaviour.

## 4.2 Research approach

This section discusses the approach taken to implement this doctoral research project and thus answer the research questions set out in Section 4.1 above. As a practical doctoral research project, which is founded on some of the established Building Performance Evaluation (BPE) techniques discussed in Section 3.2 above, the adopted strategy is that of producing a case study, based on a series of case studies, using mixed methods to collect and analyse the data, which constitutes the evidence required to produce a case study. The BPE techniques use a combination of quantitative and qualitative data collection and analysis methods and thus have the potential to provide a comprehensive range of empirical evidence for assessing the effectiveness of retrofitted external wall insulation (EWI). To demonstrate the appropriateness of this approach, first this section sets out the justification for producing a case study from a collection of case studies using mixed methods of data collection and analysis. This is followed by an outline of the rationale for each of the adopted methods. Next an overview of the instruments used to collect the data is set out. Finally, this section concludes by discussing the population of the data used to compile the evidence for the case study.

### 4.2.1 Justification for taking a case study approach

Whilst taking a case study approach to research in the built environment is argued by Proverbs and Gameson (2009) as being an appropriate methodology, it is also argued that there is generally a lack of guidance within literature for its use within this context. However, Proverbs and Gameson (2009) have contributed to filling this gap through a practical guide to adopting this approach within built environment research. This guide has provided a valuable link to literature that has been published to provide guidance about taking a case study approach to research generally and for specific subjects, such as education. For example, Proverbs and Gameson (2009) and Simmons (2009) argue that one of the key characteristics of the case study approach is that it should tell a coherent 'story', which is based on the interpretation of the data that has been collected and analysed and thus inferences determined from this evidence.

Further characteristics of a case study include: drawing on several sources of evidence; triangulation of these sources of evidence; providing context for a research project; demonstration of detailed knowledge and understanding of issues that are central to the research, as well as a broad exploration of related issues; focusing on a particular context and thus constrained by relevant boundaries (Remenyi *et al*, 2002, cited in Proverbs and Gameson, 2009, p. 99). It is argued by Yin (2003, cited in Proverbs and Gameson, 2009, p.99) that robust results can be achieved by a consensus obtained from the triangulation of three sources of evidence. Furthermore, this evidence is often obtained using a combination of quantitative and qualitative data (ibid).

For this doctoral research project, the rationale for taking a case study approach was based on meeting these criteria of collecting and analysing at least three sources of evidence to assess the effectiveness of the retrofitted EWI at a series of Arbed I case study dwellings. In turn, these case studies collectively form an overall case study to tell the story of the Arbed I process for each dwelling involved in this doctoral research project. The story includes: the context, which is constrained by the Arbed I funding criteria, the decisions made by the housing associations and the occupant's willingness to participate in this doctoral research project; as well as provide detailed information about the EWI installations and the relevant associated issues, which could be applicable to other retrofit projects with similar dwelling types and occupancies.

### 4.2.2 Rationale for methods of data collection and analysis

From the BPE techniques identified in Section 3.2 above, the three overarching methods of data collection and analysis that have been adopted are: field observations; occupant surveys; and energy consumption monitoring. These overarching methods encompass the collection and analysis of qualitative and quantitative data obtained through specific methods relevant to this doctoral research project, which collectively allow the production of the case studies.

Furthermore, the rationale for the choices of adopted methods of data collection and analysis also centred on the background knowledge and the additional skills that were realistically achievable for the author of this thesis. As an Architectural Technologist, the author of this thesis has existing knowledge of construction forms and of the design process for undertaking construction work. In addition, the industrial partner of this doctoral research project provided funding for the author to undertake a Level One Thermography training course and exam, which was passed at a high level. Finally, the industrial partner purchased an infrared camera for use on this doctoral research project and other research projects they were supporting.

As a result, the case studies provide evidence about the retrofitted EWI in terms of construction quality and energy performance, as set out in Table 27 below. The links are that construction quality can affect the energy performance of the dwelling. To demonstrate the rationale for each of the chosen EWI assessments, the specific adopted methods for collecting the evidence, which are triangulated, are each discussed in turn. Additionally, demographic data was collected about the occupants at each of the case study dwellings to provide the necessary context for this type of research approach.

**Table 26: Data collection methods for each EWI assessment**

| Overarching methods | EWI Assessment | |
|---|---|---|
| | Construction quality | Energy performance |
| Field observations | X | X |
| Occupant surveys | | X |
| Energy consumption monitoring | | X |

### *Construction quality*

The three types of field observations adopted to assess the construction quality of the EWI installations involved collecting primary qualitative data from:

- Post-retrofit external thermographic surveys;
- Photographic recording before, during and after the installations; and
- Reviewing technical details as they were installed on site.

In addition, to support each of these data, the housing associations provided information about the procurement method used to implement the retrofitted EWI and the construction design details and specifications from the manufacturers. The rationale for obtaining information about the procurement method was to assist with providing context for assessing the construction quality as part of producing the case studies. The purpose of the post-retrofit external thermographic surveys was to identify any potential thermal bridging that has been created as a result of a lack of continuity of the retrofitted EWI, which, as discussed in Chapter Two above, is central to assessing the overall energy performance of the dwelling.

The purpose of taking photographs before, during and after the EWI installations was to provide a visual record of the retrofit process. Additionally, the photographs have been used to: illustrate improvements in the overall appearance of the dwellings; record methods of installation; assist with reviewing the technical details as they were installed on site; and aid interpretation of the external thermographic surveys. The purpose of reviewing the technical details as they were installed on site was to provide an additional record of the methods of installation and illustration of potential paths for thermal bridging. As a result, the collation of this type of data has proved to be a valuable method of linking the results from the photographic recordings and the external thermographic surveys. In addition, the review of technical details as they were installed on site have been compared to the manufacturer's details and specifications to ascertain if design intentions were achieved on site.

Another method of assessing the construction quality of the retrofitted EWI is air-tightness testing, as discussed in section 3.2. However, as the author of this thesis is not qualified to undertake air-tightness tests, to collect data using this method would have required the employment of an external professional, which would have been outside the cost constraints of this doctoral research project. Furthermore, it has been possible to identify the sources of air infiltration from thermographic survey images. Therefore it was decided that thermographic surveys, in conjunction with photographic recordings and reviews of the technical details, would be adequate for the purpose of assessing the construction quality of the EWI installations for this doctoral research project. Nevertheless, it is recognised that in an ideal situation both an air-tightness test and thermographic survey would be undertaken simultaneously to maximise the evaluation of construction quality of the retrofitted EWI.

### *Energy performance*

Assessing the energy performance of the dwellings is based on three sources of quantitative data. This quantitative data was compiled from: energy consumption monitoring involving energy efficiency calculations, which are based on pre-retrofit and post-retrofit energy usage and carbon emissions, dwelling floor area and heating degree day data; cost-effectiveness calculations, which are based on installation costs obtained from the housing associations under the umbrella of field observations; and occupant surveys to ascertain perceptions about thermal comfort and behaviour since having the retrofitted EWI installed. The purpose of obtaining data about occupant behaviour towards energy use was to identify any potential relationships to minimal or non-existent reductions of energy consumption detected in the energy performance assessments, which may have occurred and thus indicate that the rebound effect or comfort take back has occurred. For the cost effectiveness calculations, the purpose was to establish the payback period of the EWI installations, based on the capital costs relative to energy savings assessed through the energy efficiency analysis.

The purpose of the pre-retrofit and post-retrofit energy efficiency calculations was to provide a comparison of before and after energy use and carbon emissions for the dwellings. These energy consumption and carbon emissions data are supported by the addition of floor area data, which was gathered as part of the post-retrofit occupant surveys, where the data was not available from the housing associations database. Furthermore, the heating degree day data supports the energy consumption data by providing information that was necessary to allow a comparison between two different heating seasons and thus heating demand within the dwellings. The results of the energy efficiency calculations will be presented as kWh/m$^2$/year and $CO_2$/m$^2$/year for each case study dwelling, where a full set of data was collected for both pre-retrofit and post-retrofit. In addition to providing a pre-retrofit and post-retrofit comparison, these data can be compared between similar dwelling typologies and occupancies to determine a norm and thus commence the establishment of a domestic energy use benchmark; this can form part of further work after this doctoral research project has been completed.

Other methods that could have been used for assessing the energy performance of the case study dwellings, which were identified in Sections 3.2 and 3.3 above, include: in-situ u-value calculations and co-heating tests. The rationale for not pursuing these assessments is primarily based on costs. However, the rationale also includes following recommendations set out by Leaman *et al* (2010), which state that to ensure maximum cooperation from occupants, it is necessary to minimise the intrusiveness and duration of the data collection process. As discussed in section 3.2 above, in-situ u-value calculations and co-heating tests both result in considerable disruption to occupants and take between one and two weeks to undertake.

The co-heating test is particularly disruptive to both the occupants and housing associations as the dwelling needs to be empty during the test and therefore there would have been a requirement to find alternative accommodation for the occupants. Furthermore, the industrial partner for this doctoral research project requested that in-situ u-value calculations were not undertaken. The rationale for this request was that part of the Arbed I funding was based on the external walls of the dwellings having a u-value of 2.1 $W/m^2K$. Therefore, if the results of the in-situ u-value calculations had revealed that the external walls had a better u-value then there was a risk of the Arbed I funding being withdrawn.

Another method that could have been used for assessing energy performance is longitudinal studies of the internal and external environmental conditions using a data logging system. However, as discussed in section 3.2.3, the costs involved with implementing and collecting data from a single dwelling using this method are very high and thus outside the cost constraints of this doctoral research project. Furthermore, there was not an opportunity to collect pre-retrofit data due to the timing of the commencement of this doctoral research project being in line with the identification of suitable dwellings that would receive the retrofitted EWI by the housing associations. Additionally, due to the Arbed I funding requirements, the installations had to commence almost immediately upon identifying the suitable dwellings. Therefore, as it would only have been possible to collect post-retrofit data and without any pre-retrofit data to compare to, it was decided that the significant expense could not be justified for this doctoral research project. Furthermore, one of the aspirations from the outset of this doctoral research project was to evaluate as many Arbed I dwellings as possible.

#### *Demographic data*

Further evidence collected includes demographic data obtained through the occupant surveys; these provide context for the case studies for this doctoral research project. The purpose of this demographic data is to demonstrate the range of: tenures; dwelling types; age and number of occupants, within the individual case studies that make up the complete case study. Whilst these data do not constitute evidence for the evaluation of the retrofitted EWI, they provide valuable information for the production of the case studies, which is central to this doctoral research project.

### 4.2.3 Instruments used to collect the data

The instruments used to collect the data have been classified into two types: developed by the author and available to the author. The instrument that has been developed by the author is the questionnaires, which were used for the pre-retrofit and post-retrofit occupant surveys. The instruments that were available to the author for the purpose of undertaking this doctoral research project include: recording equipment; and access to internal and external databases. The internal database consists of data held by the housing associations. Whereas the external databases are from several sources, including: the local authority; a local weather station; and the EWI manufacturers.

### *Questionnaires*

As discussed in section 3.2.1 above, questionnaires are an efficient instrument for collecting data about how occupants interact and thus use their dwelling (Leaman *et al*, 2003; EST, 2009). Furthermore, this instrument can be effectively administered as structured interviews, either face-to-face or by telephone, as well as by the traditional postal method (Oppenheim, 1992). However, it was argued that employing questionnaires as structured interviews has many advantages over the postal method due to the prospect for increased: response rates; opportunities to provide explanations of questions where required; participation of people with poor literacy; and likelihood of all questions being answered (ibid). In addition, the use of a questionnaire as part of a structured interview with more than one participant within the whole research project ensures that there is consistency of the data collected (Haigh, 2008; Hopper *et al*, 2011b). Finally, asking closed questions as part of a structured interview allow quantitative data to be collected more readily, which further improves opportunities for making comparisons between two or more dwellings (ibid). Closed questions can also be asked to record attitudes by using a Likert scale and thus enable these data to be quantified (Hoxley, 2008; Hopper *et al*, 2011b).

As discussed in section 3.2.1 above, whilst there were several recommendations set out by the TSB (no date), Hamilton (2002), Leaman *et al* (2003), the EST (2009) and Sheridan (2009) for the content of the questionnaires, the initial focus for this doctoral research project was to obtain: demographic information (tenure, number of occupants, age categories, time spent in the dwelling, household income); dwelling details (type, construction, existing insulation, window types); energy use (types of appliances, energy consumption data, fuel poverty status, level of energy consciousness); heating and hot water system and control details; lighting details; ventilation details; thermal comfort perceptions; information about the behaviour of occupants towards energy use; and any changes between before and after the EWI was installed. The two questionnaires (pre-retrofit and post-retrofit) are set out in Appendices VIII and X, respectively.

However, following a review of the data collected and its usefulness for meeting the aim and objectives of this doctoral research project in its final form, as presented in this thesis, the focus of the questionnaire data presented in Chapter Five is that of: demographic information; dwelling details; and thermal comfort perceptions and behaviour towards energy use since having the retrofitted EWI installed. Thus these data have been extrapolated from all the data collected using the two questionnaires. In addition, as part of the post-retrofit occupant survey, details of the energy supplier for each dwelling and consent for making direct contact to obtain actual consumption data was requested. These additions to the post-retrofit questionnaire were due to the realisation that energy consumption data was not readily available from the occupants during the pre-retrofit occupant survey. For many of the dwellings, the occupants did not have this information due to being on a pre-payment meter. The other main reason that this energy consumption data was not available from the occupants was due to them not keeping or knowing the location of their bills.

A further change between the approach to the pre-retrofit and post-retrofit occupant surveys was that the occupants were given the option to undertake the post-retrofit survey as a postal questionnaire. The rationale for this decision was primarily due to the rapport that had been developed between the author and the occupants as part of the pre-retrofit survey. This decision was also based on the acknowledgement that it was difficult to achieve a mutually convenient time between both parties (author and occupant). Therefore it was anticipated that the response rate would be consistent with that of the pre-retrofit occupant survey using the postal method.

A further strategy that was implemented in the latter stages of the doctoral research project was to send a short postal questionnaire to all the Arbed I dwellings for CHG and FHA that had not taken part in the full pre-retrofit and post-retrofit occupant surveys. The short questionnaire was a simplified version of the full questionnaire, which only asked questions about: tenure; number and age of occupants; time spent at home; dwelling details (type and construction); retrofitted measures installed; energy consumption; energy supplier details and consent for making direct contact; and perceptions of increased thermal comfort and behaviour towards energy use since having EWI installed. This short questionnaire is set out in Appendix XI. The rationale for implementing this additional occupant survey was to increase the quantity of data collected about the Arbed I dwellings and thus extend the number of case studies to improve the robustness of the conclusions drawn from this doctoral research project.

### *Recording equipment*

The first set of the instruments that were available to the author for use on this doctoral research project were: an infrared camera; a handheld weather meter (Kestrel 3000); a digital photographic camera; Autodesk Revit Architecture CAD software; and a digital measuring tool (Disto). The infrared camera was used to capture the thermal images for the pre-retrofit and post-retrofit thermographic surveys as part of the field observations. These thermographic surveys were undertaken to compare before and after heat loss through the external walls of the Arbed I dwellings, as well as for assessing the continuity of the EWI and thus the occurrence of potential thermal bridging. The infrared camera used for the thermographic surveys, which is owned by CHG, was a FLIR B365 and has a resolution of 320 x 240 pixels.

The handheld weather was used to record the internal and external environmental conditions at the location and time of each thermographic survey. These environmental conditions included: air temperature; relative humidity; and wind speed (externally only). The digital photographic camera was used to capture visual images before, during and after the retrofitted EWI installations as part of the field observations. Autodesk Revit Architecture CAD software (2010 version) was used to produce the construction details to record the technical solutions implemented on site, also as part of the field observations. Finally, the digital measuring tool was used to measure the floor area of the dwellings, which have been used as part of the energy consumption calculations.

***Internal and external databases***

The second set of the instruments that were available to the author for this doctoral research project were: access to CHG and FHA files about the Arbed I dwellings and the EWI installations; construction details and specifications from the EWI manufacturers; and external weather data from two local weather stations. The internal data that was available to the author from CHG and FHA consisted of files about the Arbed I dwellings and EWI installations; these were provided at the commencement of this doctoral research project and consisted of:

dwelling addresses and contact details for the occupants; condition and measured surveys of the dwellings, where available; information about the measures that were being installed at each of the dwellings; information about the procurement method being employed; the details of the manufacturers that were supplying the EWI; the names of the EWI systems that were being installed; the expected date of installations; details of the contractors that were installing the EWI systems; and cost details for the EWI installations. In addition, photographs were provided by CHG from their files, which were taken during the EWI installations.

The remainder of the data that was available to the author was from external sources. Based on the information provided by CHG, the construction details and specifications from the EWI manufacturers were sourced from the technical pages on their websites, which also included certificates from the British Board of Agrément. In combination, this information provided details about how the EWI systems had to be installed, as well as any prerequisites that were required to be undertaken before and during installation. For example, the removal or treatment of any existing surface finishes that were loose.

The weather data required for this doctoral research project was obtained by the author from two external sources. The first was from a local mast, which was obtained through the local authority's website (City and County of Swansea, 2011, 2013). This weather data was used for the purpose of confirming external environmental conditions for each of the thermographic surveys. The second was from the nearest weather station that distributed heating degree day data, which was used for the purpose of normalising the energy consumption data for comparison between the two heating seasons before and after the retrofitted EWI was installed.

### 4.2.4 Population of data

Ultimately the population of data and thus the sample for the case study resulting from this doctoral research project was dictated by the willingness of occupants to participate. As a result, a non-probability sample strategy using a convenience sampling design was taken (Bryman, 2008). All occupants of Arbed I dwellings in Swansea that were listed on CHG and FHA's portfolio, at the commencement of this doctoral research project, were contacted by the author and invited to participate. Following receipt of contact from the occupants, the population of data was further constrained by their availability in line with the necessary timing for undertaking the data collection. For example, pre-retrofit thermographic surveys had to be undertaken prior to the installation of the EWI. Furthermore, following refinement of this doctoral research project during the early stages, which resulted in focussing only on dwellings that were receiving retrofitted EWI, the sample of the population concentrated on these Arbed I dwellings.

For the energy consumption data, the population was constrained by the responses received from the energy companies that supplied the corresponding Arbed I dwellings. Whilst every effort was made by the author to obtain all the energy consumption data that had been consented to collect, not all information was received from all the energy companies that were contacted. Relative to energy consumption data was the Heating Degree Day's data. This was obtained from the closest weather station that publishes Heating Degree Day data.

## 4.3 Research methods

To demonstrate the methods used to answer the research questions and thus meet the aim and objectives of this doctoral research project, this section sets out the: data collection procedures in section 4.3.1; pilot studies that were undertaken in section 4.3.2; data analysis and validity procedures in 4.3.3; and the ethical considerations that were implemented in 4.3.4. Collectively, this section provides a detailed account of the operations and actions undertaken to accomplish this doctoral research project.

### 4.3.1 Data collection procedures

This section enumerates the processes undertaken to collect the data within each of the three overarching methods: field observations; occupant surveys; and energy consumption monitoring. The tasks undertaken for each method are discussed as specific activities performed to collect the individual sets of data.

#### *Field observations*

The data collection activities that were undertaken within the remit of field observations include: taking digital photographs before, during and after retrofitted EWI installations; recording the technical solutions observed on site; pre-retrofit and post-retrofit external thermographic surveys; and acquisition of relevant information from the housing associations.

#### Digital photographs

Once the Arbed I dwellings were chosen by the housing associations, overview photographs were taken to record the pre-retrofit condition of the external facades. Upon commencement and during the installation process, detailed photographs were taken to record the methods used to install the retrofitted EWI. After the EWI was installed, photographs were taken to record the detailed and general finish of the installations. The detailed photographs that were taken, which required access on the scaffolding, were taken by CHG's Arbed I manager; this was due to health and safety reasons as the author of this thesis did not have permission from the site managers to access the scaffolding. In addition, CHG's Arbed I manager provided a copy of all their other relevant photographs to the author of this thesis.

### Observed technical details

During the retrofit process the author of this thesis observed the methods implemented for installing the EWI and recorded this information as technical details, with the aid of the photographs taken (as described above). These technical details were then drawn to scale in Revit Architecture CAD software. Due to the lack of available data for the existing (pre-retrofit) construction of the dwellings, a number of assumptions had to be made whilst producing the drawings. These assumptions are based on the methods of construction used to build dwellings in the 1900's, as set out in Chudley and Greeno (2005), which included: floor to wall junctions; wall thickness; window jamb, sill and head details; and eaves details. In addition, during the process of producing the technical details, the potential path of thermal bridging was explored and recorded on the drawings. Furthermore, these technical details provide a link between the photographs and thermographic survey images.

### Thermographic surveys

External thermographic surveys were undertaken before and after the EWI installations at seven Arbed I dwellings. These were limited to qualitative thermographic surveys to assess apparent overall reductions in heat loss through the external walls and the continuity of the retrofitted EWI. To assess the apparent overall reductions in heat loss, the pre-retrofit thermographic images of the whole facade were compared to the equivalent post-retrofit thermographic images. To assess the continuity of the retrofitted EWI and thus identify any potential thermal bridging, the post-retrofit thermographic surveys focussed upon junctions within the external facade. The junctions that were focussed upon included: the ground to wall junction; around openings; and at the eaves. In addition, the junctions between the two types of EWI, which was installed above and below the damp proof course (DPC) level, was given attention during the thermographic surveys.

The process undertaken was the same for each thermographic survey. The first task was to establish the availability of a member of staff from CHG to accompany the author of this thesis. It was necessary for a member of CHG staff to accompany the author for insurance reasons, as well as on health and safety grounds. As the infrared camera belonged to CHG, their insurance only covered the camera to be stored either at CHG's offices or at a member of staff's home. Additionally, for health and safety reasons, the author of this thesis did not work alone. The basis for this decision was due to the author of this thesis having to enter the homes of strangers and the requirement for thermographic surveys to be undertaken in the dark.

In addition, due to the location of some of the dwellings being adjacent to highways, caution had to be taken by the author of this thesis when choosing the ideal position to stand to capture the thermograms, as this was often in the middle of the road. However, it was not always possible to stand in the ideal location and therefore this limited the possibilities for capturing some thermograms. There was a further benefit of having someone accompany the author of this thesis to thermographic surveys. Chiefly, this meant that one person could focus on capturing the thermograms, whilst the other person recorded the environmental data and details about each thermogram on a form designed by the author of this thesis, as set out in Appendix XIII.

Once the availability of a member of CHG staff had been established, the second task was to check the weather forecast to determine a day with appropriate environmental conditions for undertaking the thermographic surveys. The criteria used to determine appropriate environmental conditions are set out in Table 28 below, which are based on the criteria discussed in Section 3.2.5 above. The third task was to contact to the occupants of the dwellings, either in person or by telephone, to determine their availability, as well as discuss the information about the survey, which is set out in Table 29 below. The fourth task, which was undertaken early on the day of the survey, was to check the batteries of the camera were fully charged. Where the batteries were not fully charged, they were put on charge so that they would be ready for the survey that evening.

The fifth task was to print the forms used to record the environmental data and details about each of the thermograms at the time of the survey (as set out in Appendix XIII). In addition, the date, camera and dwelling location details were recorded on the form prior to the survey. The sixth and final task undertaken prior to the thermographic surveys was to visit each of the dwellings during daylight hours to take digital photographs. The purpose of these photographs was to aid interpretation of the thermograms. These six tasks that were undertaken prior to each thermographic survey are summarised in Table 30 below.

Table 27: Environmental conditions adhered to during thermographic surveys

| Recommendation | Source |
|---|---|
| At least one hour following exposure to solar radiation on surface must elapse before survey undertaken. | Pearson (2002) |
| Survey undertaken in the dark. | Pearson (2002)<br>EST (2000 and 2005a) |
| At least 10°C temperature difference between inside and outside the dwelling during survey. | Hart (1991)<br>EST (2000)<br>Pearson (2002 and 2011) |
| The 10°C temperature difference achieved for at least four hours prior to survey. | EST (2000) |
| No precipitation during and for preceding 24 hours of survey. | Pearson(2002) |
| Maximum wind speed of 8-10 m/s during survey. | EST (2000 and 2005a)<br>Pearson (2002) |

Table 28: Information about the thermographic surveys discussed with the occupants

| Item | Discussion with occupants |
|---|---|
| 1 | Provided with an explanation of:<br>a. The purpose of the survey;<br>b. Why it had to be undertaken during the hours of darkness; and<br>c. Possible reasons for a likely change in arrangements (for example, precipitation in the preceding 24 hours). |
| 2 | Advised of the:<br>a. Date;<br>b. Time; and<br>c. Names of the Thermographer's. |
| 3 | Requested that they activate their heating at least four hours before the time of the survey (to ensure there was an adequate temperature difference between inside and outside the dwelling). |

**Table 29: Summary of tasks undertaken prior to each thermographic survey**

| Task | Description |
|---|---|
| 1 | Establish availability of CHG staff to accompany Thermographer (author of this thesis) |
| 2 | Check weather forecast to determine date with appropriate environmental conditions |
| 3 | Contact occupant of dwelling, either in person or by telephone, to determine their availability and provide additional information |
| 4 | Check infrared camera batteries on day of survey and charge if necessary |
| 5 | Print forms to record environmental data and details about each thermogram at the time of the survey (as set out in Appendix XIII) |
| 6 | Visit dwelling during daylight hours on day of survey to take digital photographs that correspond with thermograms |

### Information from housing associations

During dialogue through regular meetings, discussions and correspondence with the housing associations, information which is central to this doctoral research project was ascertained. Firstly, the number and profile of the dwellings receiving retrofitted EWI through the Arbed I scheme was acquired. The profile of the dwellings included the: location; occupant contact details (where available); tenure; dwelling type (house or flat); and floor area of each dwelling, where this data was on the housing associations' database. Secondly, the timing and process employed to implement the retrofitted EWI was established. Having knowledge of the timing of the installations was imperative for this doctoral research project to ensure that the data collection was undertaken at the correct time during the retrofit process. For example, the pre-retrofit thermographic surveys had to be undertaken before the retrofitted EWI was installed to allow a direct comparison of before and after to be made. Acquiring information about the procurement process employed by the housing associations, to implement the retrofitted EWI, was essential to provide the necessary context to the data collected and thus the case study resulting from this doctoral research project.

The third set of data obtained from the housing associations, which was central to evaluating the construction quality of the retrofitted EWI, was the construction details and specifications provided by the manufacturers specifically for the Arbed I scheme. These data were imperative for comparing design intentions to the actual installations implemented on site. Furthermore, the construction details and specifications of the EWI systems were an important aid for interpretation of the thermograms. The fourth and final set of data acquired from the housing associations was the EWI costs per dwelling; this was required to determine the cost-effectiveness of retrofitting EWI at pre-1919 dwellings with occupants in fuel poverty. The overall costs of the EWI systems have been used in conjunction with the normalised energy consumption data to calculate the payback period of the retrofitted EWI.

### *Energy consumption monitoring*

The data collected as part of the energy consumption monitoring included: energy usage obtained from each case study dwelling's supplier; greenhouse gas emissions, based on energy consumption for each case study dwelling; floor area of each case study dwelling; and the Heating Degree Days for the local geographical area. Each of these data was recorded in a spreadsheet, which was developed by the author of this thesis. As part of the spreadsheet, formulae were written to automatically calculate the energy consumption and greenhouse gas emissions per square meter of floor area, as well as normalise the data according to the heating degree days.

### Energy usage from suppliers

At the commencement of this doctoral research project it was anticipated that the energy consumption data for each case study dwelling would have been obtained from the occupants with reference to their energy bills. However, during the pre-retrofit occupant surveys it quickly became apparent that it was not going to be possible to acquire the energy data through this method. The majority of the occupants were either on pre-payment meters and therefore did not receive energy bills or did not keep their energy bills once they had paid them. As a result, it was decided that as part of the post-retrofit occupant surveys that details about each of the occupant's energy suppliers and permission to contact them direct would be collected.

Once energy company details and consent had been obtained from each of the occupants, the author of this thesis then collated the data with the dates of the retrofitted EWI installations; this was to determine the 12 month period either side that energy consumption data was required. Following this, the author of this thesis contacted each of the energy companies to commence the process of collecting the energy consumption data. Altogether five energy companies had to be contacted for data. Of these five energy companies, four obliged with the data requested and provided this using the units kilowatt hours (kWh) for both electricity and gas, where applicable. The fifth never did respond. Ironically this was the parent company providing the service of principle contractor for the Arbed I scheme in Swansea.

Each energy company was supplied with a copy of the consent form for their corresponding customers. Three of the energy companies were happy to receive this information by email and the other two requested this to be sent to them in the post. The two requests sent in the post were sent using recorded delivery and marked *'Private and confidential'*. However, one of the energy companies, which supplied the majority of the case study dwellings, took over six months to provide the data. During these six months, it took no less than five phone calls and 11 emails to chase for the data before it arrived. Furthermore, the consent forms and corresponding dates for the requests had to be sent twice during this six month period.

### Greenhouse gas emissions

Once the energy consumption data had been collected, the corresponding greenhouse emissions were calculated using conversion factors supplied by the Carbon Trust (2013). For electricity the conversion factor is 0.44548 per kWh and for natural mains gas the conversion factor is 0.18404 per kWh. The result of the calculation is given as kilograms of carbon dioxide equivalent ($KgCO_2e$). Therefore, for example if a dwelling utilised 4000 kWh of natural mains gas, they would be responsible for 736.16 $kgCO_2e$ of greenhouse gas emissions.

### Floor area

Where the floor area data was not held by the housing associations on their databases, this was collected as part of the post-retrofit occupant surveys. To collect this data, first a sketch of the floor plan was drawn of the dwelling. This was followed by measurements collected using a digital measuring tool (Disto). The area of each room was then calculated by multiplying the width by the length, along with subtracting any protruding areas, such as from staggered external walls. The complete dwelling floor area was then established from the cumulative area of each room within the dwelling.

### Heading Degree Days

As discussed in section 3.2.2, one method of utilising heating degree day data is for normalising energy consumption data, which is the purpose of collecting this data for this doctoral research project. The heating degree days data was collected from a weather station located in the Mumbles, which is approximately six miles from the case study dwellings documented in this thesis. To normalise the energy data using the heating degree days, the cumulative energy consumption for the 12 months prior to the EWI being installed was divided by the number of heating degree days for the same 12 months to ascertain the kWh per heating degree day; this was then multiplied by the 20 year average annual heating degree day to establish the normalised annual energy consumption. To normalise the energy consumption data, the calculation is illustrated as follows:

$$Normalised\ energy\ consumption\ (kWh) = \left(\frac{Annual\ energy\ consumption\ (kWh)}{Annual\ heating\ degree\ days}\right) \times 20\ year\ average\ heating\ degree\ days$$

**Figure 2: Calculation to normalise energy consumption data**

This calculation was then repeated with post-retrofit data and the difference established; this was determined by deducting the normalised pre-retrofit energy consumption from the normalised post-retrofit energy consumption. Where the result was a negative figure, this demonstrated that energy consumption had reduced. However, where the result was a positive figure, this denoted that no savings had been made.

### *Occupant surveys*

Pre-retrofit and post-retrofit occupant surveys were developed by the author of this thesis and utilised to ascertain data about each case study dwelling; this data included: demographic information about the occupants; dwelling details; and thermal comfort perceptions and behaviour towards energy use since having the retrofitted EWI installed. As discussed in section 4.2.3 above, originally the occupant surveys were designed to collect significantly more data about the case study dwellings. However, as is typical with many research projects, the revision of the aim and objectives during this doctoral research project has resulted in only the revised relevant data being extrapolated from the occupant surveys.

#### Pre-retrofit occupant surveys

The process undertaken to implement the pre-retrofit occupant surveys consisted of six tasks. The first task was to develop the pre-retrofit questionnaire, which is set out in Appendix VIII. To support the questionnaires, a letter inviting occupants to register their interest in taking part, reply slip, participant information sheet and consent form was produced. These supporting documents are also included in each of the corresponding appendices, as above. Collectively, the purpose of these supporting documents was to provide the occupants with the necessary information for them to make an informed decision about participating in this doctoral research project. Once the questionnaire and supporting documents had been developed, the second task was for author of this thesis to submit them with an application form to CMU's Cardiff School of Art and Design's ethics committee for approval. The ethics application for the pre-retrofit occupant surveys is set out in Appendix IX.

The third task was to send the invitation letter and reply slip, along with a pre-paid return envelope provided by each of the corresponding housing associations, to each of the Arbed I dwellings. However, after the lack of response from a fellow researcher's postal questionnaire sent to some of CHG's proposed Arbed I dwellings, it was decided to wait until the occupants knew that the works were definitely going to be undertaken before sending out the invitation letters. The invitation letter briefly explained the purpose of this doctoral research project and requested that they complete the reply slip with their contact details and return it in the pre-paid envelope, if they were interested in taking part. It was stressed in the invitation letter that the occupants were not committing themselves to participating in the research by returning the reply slip. Upon receipt of the reply slips it was stated that they would be contacted using their preferred method (telephone or letter) to provide them with more information and allow them to make an informed decision about taking part.

Once the reply slips had been received, the fourth task was to contact each of the occupants to provide them with additional information about this doctoral research project, which was taken from the participant information sheet, and what their involvement would entail so that they could decide if they wanted to take part. All of the occupants that were contactable agreed to take part. For the occupants where a mutually convenient time could be arranged, appointments were made to visit the occupants in their homes to complete the pre-retrofit questionnaire, which was the fifth task undertaken. At each of the structured interviews, the author of this thesis was accompanied by a fellow researcher from

CMU or the Arbed I liaison officer from the external project manager's organisation, as discussed in section 1.6 above.

At the commencement of the structured interview, the occupant was provided with a copy of the participant information sheet and each section was discussed in turn. The occupant was then asked if they had any questions and if they would be happy to sign the consent form. A copy of the consent form was also provided for the occupant to keep for their records, to accompany the participant information sheet. After completing the consent form, the questions on the questionnaire were then asked, each in turn. Throughout the interview, occupants were given every opportunity to ask for an explanation of any questions they did not understand. At the end of the interview, each occupant was asked if they would be happy for the author of this thesis to return after they had the EWI for a complete winter heating season. The response to this question was recorded at the end of the questionnaire. The sixth and final task for the pre-retrofit occupant surveys was to collate the data into a spreadsheet.

#### Post-retrofit occupant surveys

The post-retrofit questionnaires were developed approximately nine months after the pre-retrofit occupant surveys commenced, which was the first task undertaken at the post-retrofit stage. The advantage of taking this approach was that the lessons learnt during the implementation of the pre-retrofit occupant surveys were incorporated into the post-retrofit occupant surveys. As discussed in section 4.2.3 above, the lessons learnt included: identifying that many occupants were unable to provide the energy consumption data that was required for this doctoral research project; realising that the rapport developed with the occupants during the pre-retrofit occupant surveys could be positively exploited during the post-retrofit stage by offering the option to utilise a postal method, which allowed the questionnaire to be completed at a more convenient time for the occupants.

As discussed in section 4.2.3 above, two post-retrofit questionnaires were developed to aid meeting the goal of collecting as much empirical data as possible about the Arbed I dwellings in Swansea. The full post-retrofit questionnaire is set out in Appendix X and the short postal version is set out in Appendix XI, along with the corresponding supporting documents. For the both post-retrofit questionnaires the supporting documents were updated: participant information sheets, which explained the purpose of this doctoral research project; and consent forms, which included permission to contact the occupant's energy supplier and to measure the floor area, where this data was not already held by the corresponding housing association.

The second task was to gain ethics approval for the post-retrofit questionnaires and supporting documents. Both the full and short postal questionnaires and supporting documents were included in one ethics approval application, which is set out in Appendix XII. The third task was to contact all the occupants that had participated in the pre-retrofit occupant survey and arrange a second appointment to undertake the post-retrofit occupant survey. Due to the rapport that had been developed with the occupants during the pre-retrofit occupant surveys, an offer of posting the full questionnaire was given where a mutually convenient appointment could not be arranged. In addition, as part of this third task, the short post-retrofit questionnaire was sent to all of the CHG's and FHA's Arbed I dwellings in Swansea, which had not taken part in the pre-retrofit occupant surveys.

The fourth task was to undertake the post-retrofit structured interviews with all the occupants where a mutually convenient appointment was made. As with the pre-retrofit occupant surveys, the structured interviews commenced with handing over the participant information sheet, along with an explanation to recap the purpose of this doctoral research project and to give an opportunity for the occupant to ask any questions. In addition, the occupant was requested to complete the consent form, to which a copy was provided. During the interview, occupants were given every opportunity to ask any questions, where they required further clarification of the information being requested. Following the interview, the floor area of the dwelling was measured, where this data was required due to not being held on the housing associations' database. Following the completion of the post-retrofit occupant surveys, the fifth and final task was to add and thus collate the data onto the spreadsheet that was set up for the pre-retrofit occupant surveys.

### 4.3.2 Pilot studies

In preparation for the data collection, two pilot studies were undertaken. The first was for the occupant surveys and the second was for the thermographic surveys. The process undertaken for each of these pilot studies are set out in this section below.

#### *Occupant surveys*

To test the types of questions contained within the questionnaires developed for the occupant surveys, a focus group was undertaken at CHG's offices using a fellow researcher's questionnaire. As discussed in section 4.3.1 above, a fellow researcher attempted to collect data from some of the Arbed dwellings and the majority of the questions were the same as for the questionnaire used for this doctoral research project. These questions were subsequently tested during the focus group, which was held at CHG offices on Wednesday 11th August 2010. The members of the focus group were invited by CHG. However, it was not possible to test the robustness of the energy consumption due to participants not taking their energy bills to the focus group. Nevertheless, in the end the energy consumption data was collected directly from the occupant's energy suppliers, as discussed above in section

#### *Thermographic surveys*

To test the process for undertaking thermographic surveys, a pilot study was executed with Professor Steve Goodhew of Plymouth University. Prof. Goodhew is an expert in thermography and offered to provide guidance to the group of researchers at CMU following the training undertaken. The thermographic survey was undertaken at one of CHG's new build apartment buildings. The thermographic survey was predominantly undertaken inside the one apartment. However, external thermal images were also undertaken as part of the pilot study. The pilot study provided an opportunity to practice with all the functions on the camera, as well as capturing the images. In addition, Prof. Goodhew provided guidance for interpreting the thermograms.

### 4.3.3 Data analysis and validity procedures

For each case study there are three sets of data for each of the EWI assessments, construction quality and energy performance, to maximise the robustness of the data analysis. This section thus sets out the structure of the analysis of the data for the case studies.

### *Construction quality*

As set out in section 4.2.2, in addition to the qualitative data from the EWI construction details and specifications produced by the manufacturers, the three primary field observations for assessing the construction quality involved the collection of qualitative data through: photographic recording before, during and after the EWI installations; reviewing the technical details implemented on site; and pre-retrofit and post-retrofit external thermographic surveys. These data are triangulated as shown in Figure 3 below. The results of the data analysis of two of the sets of data provide evidence to support inferences ascertained from the third. Therefore, external thermographic survey and photographic data analysis provide evidence to support inferences from the analysis of reviewing the technical details. Secondly, the analysis from reviewing the technical details and photographic recording provide evidence to support inferences from analysis of the external thermographic surveys. Finally, the analysis of external thermographic surveys and review of technical details provide evidence to support inferences from analysis of the photographic recordings.

The process undertaken to analyse the three sets of construction quality data involved reviewing the photographs, technical drawings and thermal images to check the continuity of the EWI and identify any potential thermal bridging. The photographs provide an overview and thus good indication of the locations of potential issues with the EWI installations. These issues were subsequently listed as part of the analysis of the photographs. Whilst producing the technical details it was possible to identify and illustrate on the drawings where the potential paths for thermal bridging were located within the EWI installations. For the thermograms, the analysis of these images involved two stages.

The first task was to thermally tune the images to increase the accuracy of the thermal patterns being displayed, which involved setting the temperature range and palette. The recommended temperature range for external thermograms is 5°C below the ambient air temperature and up to 10-15°C above the lowest temperature (Faulkner, 2013). For thermographic building surveys, it is recommended that the 'Rainbow' palette is used (ibid). With the Rainbow palette, once thermograms are thermally tuned, warmer surfaces are displayed as reds and yellows. Whilst colder surfaces are shown as blues and purples. Green colours indicate that the surface is consistent with the ambient air temperature.

Once the thermograms had been the thermally tuned, the second task was to interpret the images. For external thermograms, the interpretation involved identifying warmer areas of the external walls of the dwellings, which indicates heat loss, either due to a lack of continuity of the EWI or residual thermal bridging. Collectively, the analysis of all three sets of data confirmed the location of these issues within the external walls.

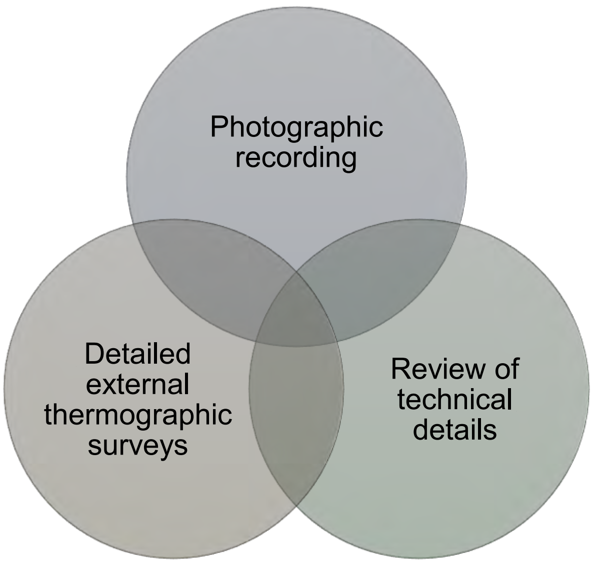


**Figure 3: Triangulation of data to assess construction quality of the retrofitted EWI**

### *Energy performance*

The three primary sources of quantitative data for assessing the energy performance of the case study dwellings includes: energy consumption monitoring; costs of the EWI installations; and occupant thermal comfort and behaviour data. These data are triangulated as shown in Figure 4 below. As with assessing the construction quality of the retrofitted EWI, the results of the data analysis of two sets of energy performance data provide evidence to support inferences ascertained from the third. Therefore, analysis of the energy consumption and occupant thermal comfort and behaviour data provides evidence to support inferences for analysis of the cost-effectiveness of the retrofitted EWI. Secondly, the costs associated with retrofitting EWI and occupant thermal comfort and behaviour data provides evidence to support inferences for analysis of the energy consumption data. Finally, the costs associated with retrofitting EWI and energy consumption data provides evidence to support inferences for analysis of the occupant thermal comfort and behaviour data.

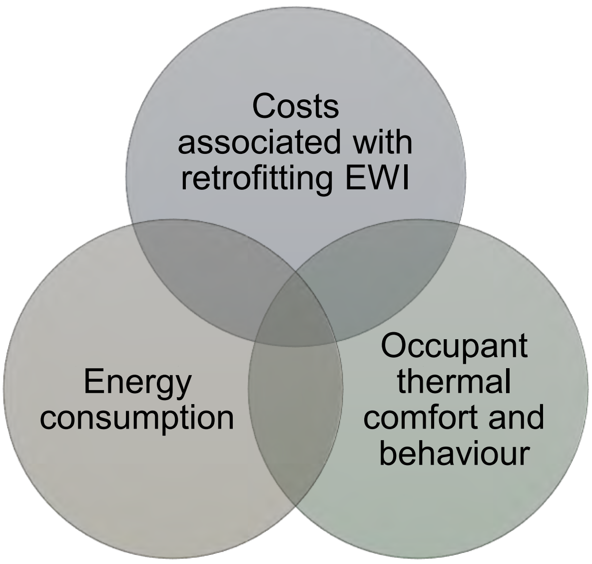


**Figure 4: Triangulation of data to assess the energy performance of the retrofitted EWI**

The process undertaken to analyse the three sets of energy performance data involved collating each of the thermal comfort and behaviour, energy consumption and costs to ascertain the effects of the retrofitted EWI. For the thermal comfort and behaviour data, which was collected using the post-retrofit occupant surveys, the answers to the questions were collated into a table and then presented as percentages in a pie chart. The normalised energy consumption data, together with the normalised resulting carbon emissions, are set out in a table presenting the pre-retrofit, post-retrofit and difference as percentage within a table for each case study dwelling.

In addition, to provide context for each of the case study the results of the occupant surveys questions about thermal comfort and behaviour are presented. These results are then summarised in a graph to demonstrate the overall energy consumption changes as percentages. Finally, using the same format, the cost-effectiveness of the retrofitted EWI was analysed using a table for each of the case study dwellings, for which there is data. This was then summarised at the end using a graph to demonstrate the effect on the occupant’s energy bills as percentage changes. This was then followed by a summary of the costs for installing the EWI, which was combined with the occupant’s energy costs to calculate the payback.

## Chapter summary

The purpose of this chapter was to set out the adopted methodology for this doctoral research project. Commencing with an overview of the gaps in knowledge identified in the literature review, this chapter set out the aim and objectives of this doctoral research project. This was followed by the research questions, which when answered allow the aim and objectives to be met. The research questions consisted of an overarching research question, which encapsulated the entire doctoral research project, and four sub-questions. These sub-questions were then further broken down in very detailed questions. This was then followed by the adopted research approach, which would allow the research questions to be answered.

The research approach included: the justification for using a case study approach; the rationale for the methods of data collection and analysis; the instruments used to collect the data; and how the data would be populated. It was demonstrated that by following the basic principles of producing a case study, this approach provides a robust method for telling the story of the Arbed I scheme in Swansea. The story is to be made up from individual case studies that collectively make up the entire case study as a whole. The overarching methods used to collect data from the case studies are: field observations; occupant surveys; and energy consumption monitoring. Collectively, these data will provide evidence about the construction quality and energy performance of the case study dwellings.

The final section of this chapter set out the research methods, which included: the data collection procedures; pilot studies undertaken; and the data analysis and validity procedures. The data collection procedures encapsulated within field observations included: taking digital photographs; producing technical details; undertaking thermographic surveys; and collecting information from the housing associations. For the energy consumption monitoring, this included: collecting data from the occupant's energy suppliers; calculating greenhouse gas emissions; collecting floor area measurements; and utilising heating degree days to normalise the data. Finally, the occupant surveys consisted of pre-retrofit and post-retrofit structured interviews using questionnaires. Two pilot studies were discussed; these were for occupant surveys and thermographic surveys. Finally the data analysis and validity procedures set out the process undertaken to establish inferences from each of the construction quality and energy performance data. The results set out Chapter Five below follow the same structure, reporting the findings for each of the construction quality and the energy performance separately. This is also support by demographic data for the case studies to provide context for the case study.

# Chapter 5: Results

# Chapter 5: Results

Using the methods discussed in Chapter Four above, this chapter sets out the data that has been collected. Commencing with setting the scene for the case study, section 5.1 describes the demographic profiles of the Arbed I dwellings, which have contributed to this doctoral research project and thus provide the context of the individual case studies that make up the entire case study as a whole. Section 5.2 illustrates the three sets of data that was collected to evaluate the construction quality of the retrofitted EWI at the Arbed I case study dwellings. Finally, section 5.3 concludes this chapter by detailing the three sets of data that was collected to assess the energy performance of the Arbed I case study dwellings before and after the retrofitted EWI was installed. Whilst inferences from the evidence illustrated in this chapter are fully discussed in Chapter Six, each set of data are analysed as part of detailing the results in sections 5.2 and 5.3 in this chapter.

## 5.1 Demographic profiles of the case study dwellings

As part of the occupant surveys, demographic profiles have been compiled for the Arbed I case study dwellings. From the initial 198 invitation letters that were posted to the Arbed I dwellings across both housing associations, 37 reply slips were received with occupants registering their interest in taking part in this doctoral research project; this represents a 15% response rate. From the replies received, contact was established with 29 occupants. In addition, contact was made with occupants at a further two dwellings through knocking on doors to neighbours whilst visiting these 29 dwellings. In total, it was possible to make mutually convenient appointments with 31 occupants to undertake the pre-retrofit occupant surveys as structured interviews.

However, due to a number of occupants relocating to different dwellings or not being able to re-establish contact after the following heating season, only 15 occupants took part in the full post-retrofit occupant surveys as structured interviews. Additionally, as part of the post-retrofit occupant survey process, 200 short questionnaires were posted to the remaining Arbed I dwellings from the two housing associations lists, which did not take part in the structured interviews. The additional 33 dwellings were as a result of further funding received by one of the housing associations to retrofit EWI through Arbed I. Of the 200 postal questionnaires sent, nine were completed and returned; this represents a 4.5% response rate. Thus in total, occupant surveys of one form or another were completed for 40 Arbed I dwellings.

Collectively the demographic profiles, which are described in this section, provide category details about the types of dwellings, as well as the occupants who live in them. The purpose of this demographic data is to provide the context for the case study resulting from this doctoral research project. The demographic profiles have been categorised according to the dwelling type, which are relative to: geographical location of the dwellings; tenure of the occupants; number of occupants; and age of occupants. This demographic data are set out in Figures 5 to 8 below. Throughout this chapter, each case study has been given an identification letter or number so as to protect the anonymity of the participants, which is in accordance with the ethical approval granted from CSAD's ethics committee and thus agreement made with the occupants at the time of the occupant surveys, as set out in Appendix VIII, IX, X, XI and XII.

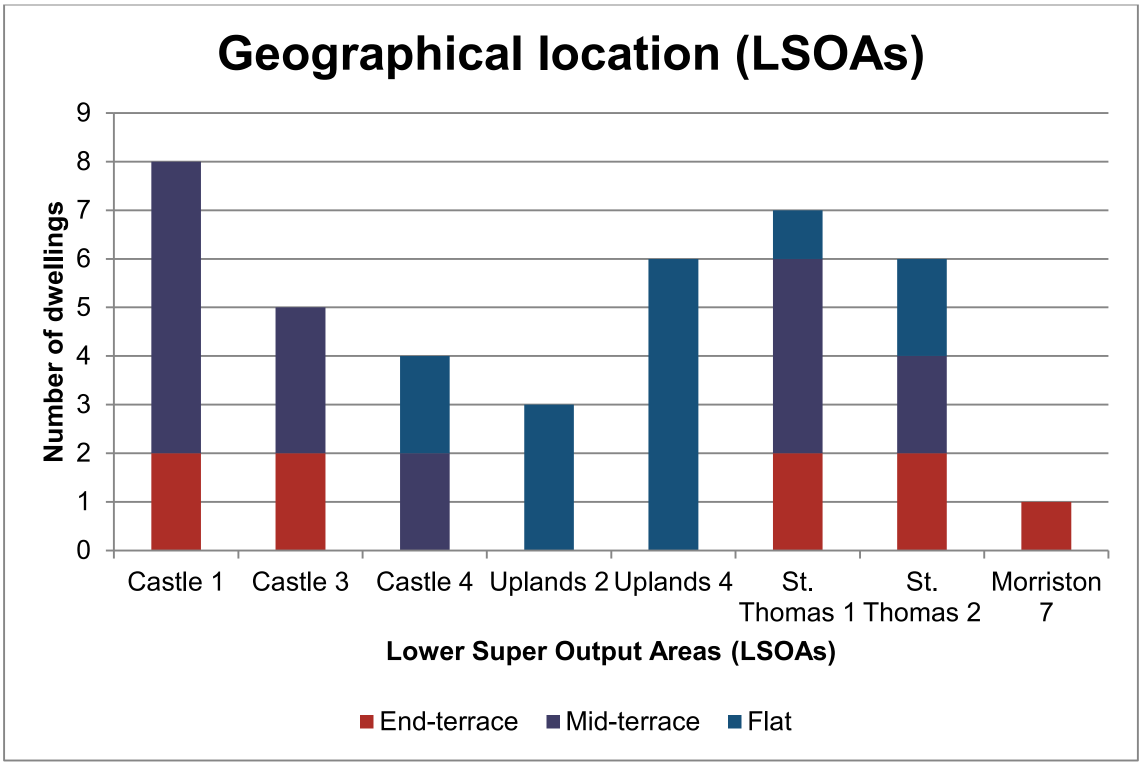


Figure 5: Geographic locations of case study dwellings according to dwelling typology

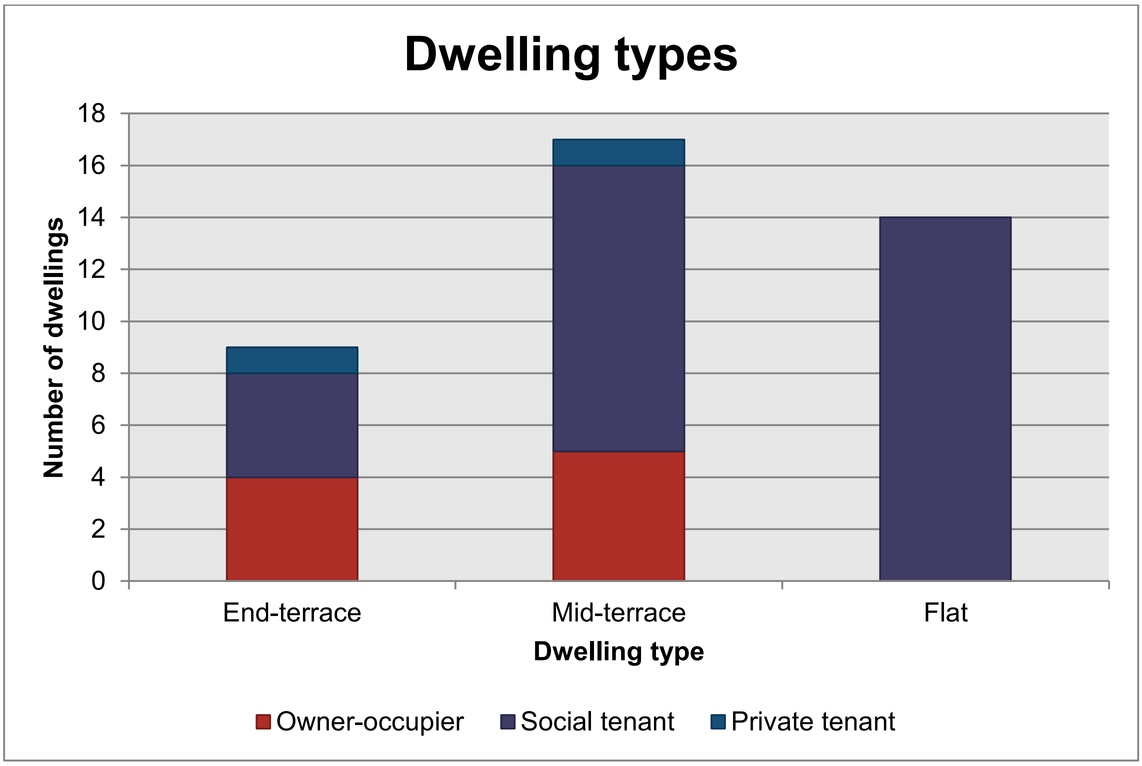


Figure 6: Types of case study dwellings according to tenure

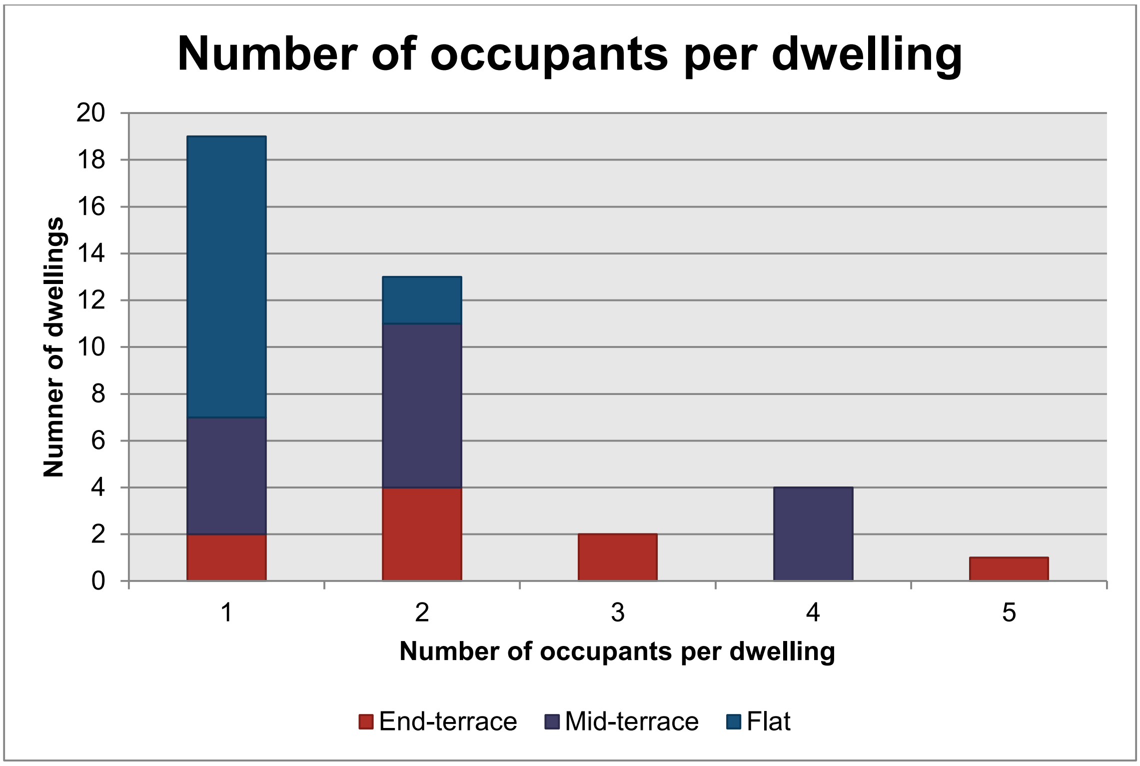


Figure 7: Number of occupants per case study dwelling according to dwelling type

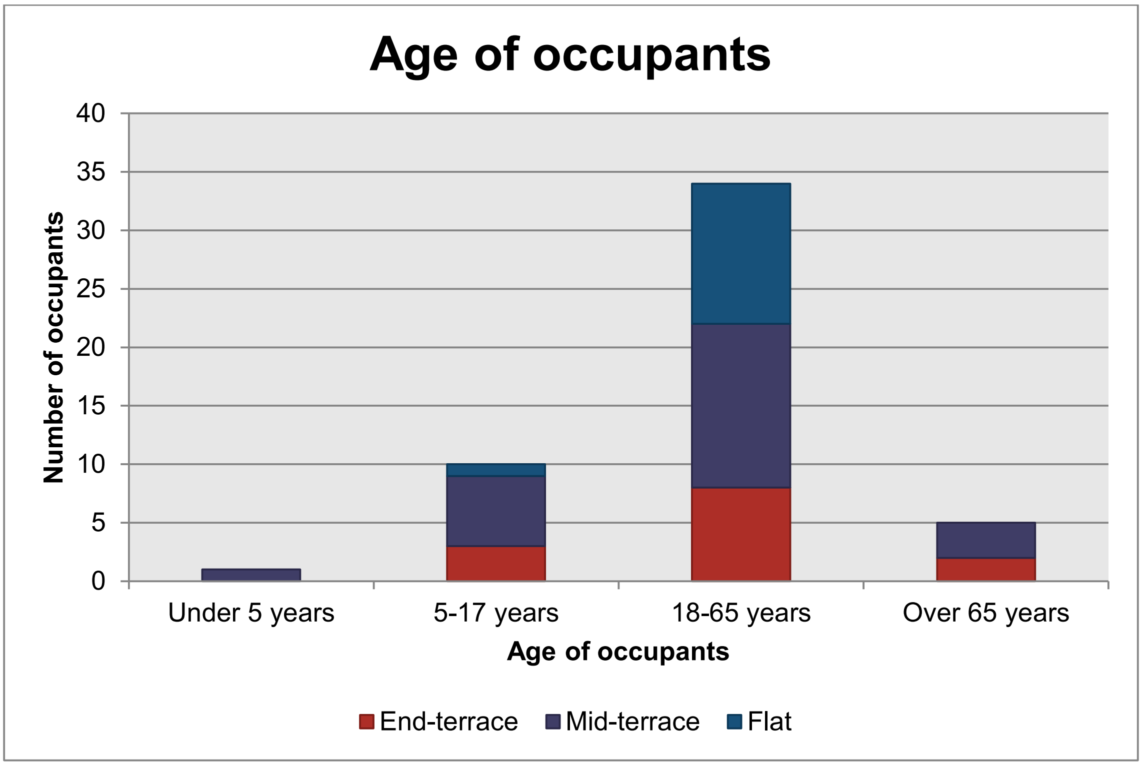


Figure 8: Age of occupants at case study dwellings according to dwelling type

## 5.2 Construction quality

This section of the results presents the field observations that were undertaken, which illustrates the qualitative data collected to evaluate the construction quality of the retrofitted EWI at the Arbed I case study dwellings. The three sets of qualitative data that make up the field observations for evaluating the construction quality include: photographs taken during and after the installations to record the methods of execution and the finished product, respectively, in section 5.2.1; the technical details that were observed and thus technical solutions implemented at the main construction junctions in section 5.2.2; and pre-retrofit and post-retrofit thermographic surveys that were undertaken to compare heat loss, as well as identify potentially induced thermal bridging at the main construction junctions in section 5.2.3.

### 5.2.1 Photographs

To provide an overview of the methods of execution and the finished product of the retrofitted EWI, this section presents the photographs that were taken during and after the installation process. The rationale for the choice of photographs presented in this section is to provide a series of images to illustrate the range of issues that were observed as part of this doctoral research project. These photographs were taken by the author of this thesis, as well as CHG's Arbed project manager. To get the story started, the first photograph shown in Figure 9 is of two dwellings where the scaffolding has been erected in preparation for the installations.

Figure 10 shows the early stages of the installation of the retrofitted EWI at ground floor level. The external facade of the dwelling in Figure 10 was in a very poor state of repair prior to the retrofitted EWI being installed. In addition, the dwelling in Figure 10 had received new windows immediately prior to the installation of the retrofitted EWI. However, despite this the retrofitted EWI was not installed at the window reveals due to the insufficient space around the window frames. This could have been avoided and the reveals could have been insulated, had there been better coordination at the planning stage.

**Figure 9: Two dwellings being prepared for the retrofitted EWI installations**

**Figure 10: Early stages of the retrofitted EWI being installed at ground floor level**

Figure 11 illustrates the installation of the retrofitted EWI at first floor level. Due to the row of terraced dwellings being on the same level, it was possible to have a continuous run of EWI installed at each floor level at the same time, which illustrates the benefits of economies of scale when taking a whole street approach. Figure 12 demonstrates one of the issues that were encountered at many of the pre-1919 dwellings, which received retrofitted EWI as part of the Arbed I scheme. The external wall with the door is for an extension and the window is in the external wall of the original dwelling. However, due to the location within the external walls of each of the openings, there was not enough space to install the retrofitted EWI. Furthermore, this was not identified until the installation stage of the process. As a result, the area of the external wall circled in Figure 12 had to remain un-insulated and thus a thermal bridge was created. If retrofitted EWI had been installed in this area of the external wall, the occupant would not have been able to open their window.

**Figure 11: Early stages of the retrofitted EWI being installed at first floor level**

**Figure 12: Retrofitted EWI being installed around a window and door opening**

Figure 13 shows the retrofitted EWI being installed at the eaves of a dwelling. In addition, this photograph illustrates how the EWI was installed around the top of a first floor window, which is very close to the eaves. Figure 14 illustrates the retrofitted EWI receiving the base coat of the rendering system. Together with Figures 10 above and 15 below, these photographs demonstrate that a whole street approach to retrofitting terraced dwellings resulted in each stage of the installation process being completed before commencing the following stage.

Figure 13: Retrofitted EWI being installed at the eaves of a dwelling

Figure 14: Retrofitted EWI receiving a base coat of the rendering system

Figure 15 shows two dwellings after the base coat stage of the rendering system has been completed as part of the retrofitted EWI installation process. Figure 16 illustrates the retrofitted EWI receiving the base coat of the rendering system at an external wall to window junction. At this junction it appears that the EWI could not be fully installed to the window due to how close the frame is to the returning wall, which are the same circumstances as that shown in Figure 12 above.

Figure 15: Retrofitted EWI after receiving base coat of rendering system

Figure 16: Retrofitted EWI receiving the base coat of the rendering system at an external wall to window junction

Figure 17 illustrates the technical solution employed at the stone window sills, as part of the retrofitted EWI system. EWI boards have been fixed to the front of the window sill to maintain the original projection. As part of achieving the required finish, corner beads have been fitted to all the external edges of the window sill, as well as to the reveals. The finishing coat of the rendering system commences at the reveals of openings. The chosen finish at the reveals of openings and the window sills was a smooth, acrylic based render. Figure 18 shows the bottom of the same window that is illustrated in Figure 16 above. As discussed above, the EWI could not be installed to the opening. If the EWI had been installed to the opening, the occupant would no longer be able to open the window. In addition, the technical solution where there was a PVC window sill is illustrated. As a new PVC window sill was fitted as part of the installation process, the EWI was installed up to its base. Whereas where the stone sills were retained, only the front of the sill received EWI boards and not the top and the bottom of the sill.

**Figure 17: Ground floor stone window sill after receiving retrofitted EWI and base coat of rendering system**

**Figure 18: Retrofitted EWI receiving base coat of rendering system below PVC window sill at external wall to window junction (same window as shown in Figure 12)**

Figure 19 illustrates the retrofitted EWI detail that was employed at a gable wall and eaves junction. Figure 20 shows the retrofitted EWI at an external wall to eaves junction where two terraced dwellings are at different levels. In both Figures 19 and 20, a capping profile was fitted to the top of the insulation with the aim of providing protection against water ingress due to the omission of any roof overhang, both at the gable and eaves.

**Figure 19: Retrofitted EWI detail at a gable wall and eaves junction**

**Figure 20: Retrofitted EWI detail at an external wall to eaves junction where two terraced dwellings are at different levels**

Figure 21 shows the eaves of a dwelling where new a new fascia and gutter has been fitted as part of the retrofit process. At first glance, it appears that the gutter has been installed to follow the roof line at the eaves. However, the roof line at the eaves is not sloping and the gutter has actually been installed incorrectly. Figure 22 illustrates the window sill and reveal after receiving the finishing coat of the render system. This photograph illustrates the different finish that was applied in these areas of the window, as well as how the projection of the sill was maintained.

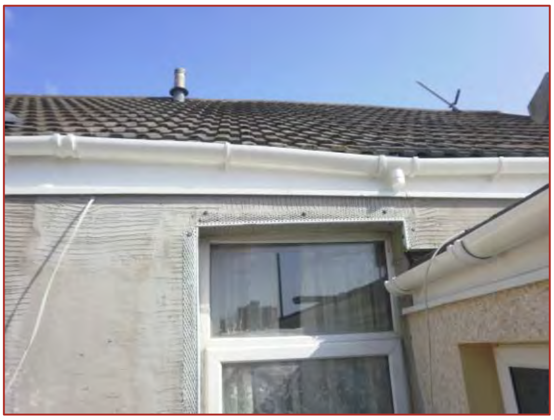

Figure 21: New fascia and gutter fitted as part of the retrofit process

Figure 22: Window sill and reveal after receiving the finishing coat of the render system

Figure 23 illustrates an eaves and verge junction between two dwellings, where the dwelling in the left of the photograph is at a higher elevation than the dwelling on the right. The verge board, fascia and gutter were all replaced as part of the retrofit process. Figure 24 shows the resulting finish of a small area of an external wall where EWI could not have been installed due to the location of the window on the adjacent wall, which can be seen in the right of the photograph. If the area had been insulated with EWI, the occupant would not have been able to open the window. However, it appears that the capping profile above the EWI on the adjacent wall may also prevent the window from being fully opened. In addition, the area left un-insulated has not been re-rendered to match the rest of the new surface finish.

Figure 23: Eaves and verge junction between two dwellings

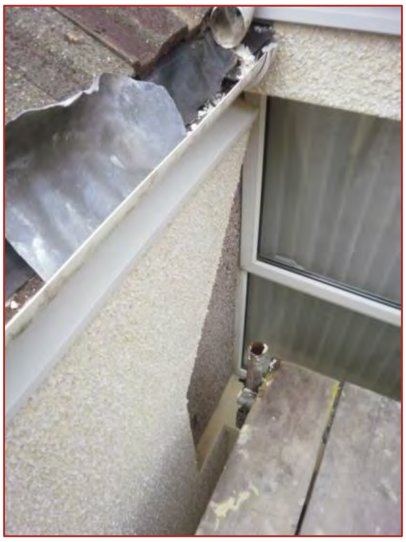

Figure 24: Gap in retrofitted EWI to allow occupant to open window

Figure 25 shows an existing gutter that remained in place during the installation of the EWI. As a result, the EWI was cut around the gutter and thus has ended up embedded into the insulation. Figure 26 illustrates the junction of the capping profile fitted below the fascia board at the eaves and the verge. The junction has been achieved by lapping the two capping profiles and it appears that the joint has not been sealed.

Figure 25: Existing gutter embedded into the EWI

Figure 26: Capping profile junction between the eaves and verge

Figure 27 illustrates the same junction as shown in Figure 26. However, in Figure 27 the photograph was taken from the adjacent angle. From this angle, it appears to confirm that the lapping joint has not been adequately sealed to provide the protection from water ingress into the top of the EWI. Figure 28 illustrates a small area of EWI which has been left exposed to the weather elements. This appears to have occurred due to the new fascia board having been cut too short to cover the EWI or the render finish having not been applied.

**Figure 27: Capping profile junction between eaves and verge at the same dwelling shown in Figure 22**

**Figure 28: Exposed EWI due to fascia board being cut too short and omission of render finish**

Figure 29 shows an eaves and verge junction at a gable wall. Despite a new fascia board and gutter being fitted as part of the retrofit process, they were not continued to the edge of the gable wall, nor was the capping profile at the verge continued to the front edge of the EWI. In addition, a gap was left between the fascia board and the small section of EWI fitted to the side. As a result, rainwater can penetrate the EWI in all of these locations. Figure 30 illustrates how EWI was installed above a first floor window. Prior to the EWI being installed there was a decorative feature as part of the head of the window, which the fascia board was cut around. However, the fascia board was not replaced as part of the retrofit process and therefore the gap where the decorative feature above the window was, has removed.

**Figure 29: Eaves and verge junction at a gable wall**

**Figure 30: EWI installed above window**

Figure 31 shows another verge and eaves junction at a gable wall. In addition, the photograph illustrates a downpipe to gutter junction. As with Figures 28 and 29, the new fascia board does not continue to the edge of the EWI on the gable wall. However, the gutter and capping profile were continued to the edge of the gable wall. Nevertheless, the capping profile had to be cut to allow the downpipe to be fitted. Figure 32 illustrates a verge junction at the ridge of the roof on a gable wall. The decorative feature that hung vertically on the gable wall at the ridge was not removed as part of the retrofit process. Instead it was swung to one side and left in place.

**Figure 31: Verge and eaves junction with downpipe connection to the gutter**

**Figure 32: Verge junction at the ridge of the roof on a gable wall**

Figure 33 shows the drip bead detail at a single storey roof abutment junction with an external wall. However, the new drip bead has been installed at a higher level to the existing and therefore the latter can still be seen. Figure 34 illustrates a telecommunication junction box located in front of an external wall on a pavement. Whilst there was enough space behind the junction box for the EWI, there was not enough space for the render system to be applied to provide the weather protection required.

**Figure 33: Drip bead detail at a single storey roof abutment junction with an external wall**

**Figure 34: Telecommunications junction box located in front of an external wall**

Collectively these photographs provide invaluable information for producing the observed technical details of the main critical junctions when retrofitting EWI.

### 5.2.2 Observed technical details

As part of the field observations undertaken, the technical details, as installed on site, were drawn in Revit Architecture CAD software (2010 version). It should be noted that these technical details are not to scale. The technical details were produced using a combination of the observations made on site and the manufacturer's specifications. The purpose of the technical details is to provide a 'cut-through' illustration of the methods implemented on site to install the EWI at four main junctions: external wall to pavement; window sill; reveals; and eaves.

However, a number of assumptions had to be made about the hidden construction elements of the existing dwellings. Due the age of the dwellings (pre-1919), these assumptions are based on traditional construction methods, as published by Chudley and Greeno (2005). As part of the analysis of these four junction details, potential paths for thermal bridging was identified and thus set out in the drawings. To aid understanding of these details, each of the corresponding details produced for the housing association by the manufacturer, as part of the design and build contract, are set out in Appendix XIV. Where these were not available, the manufacturer's details produced as part of the British Board of Agrément (BBA) certificate were used.

Figure 35 illustrates the technical solution implemented at the eaves junction, as observed on site. All of the case study dwellings have flush eaves and therefore this detail was applied to all of the retrofits observed as part of this doctoral research project. One feature of the technical detail is the identification of the potential path for thermal bridging. Due to the likely difference between the ceiling height and thus level of loft insulation, there appears to be a significant risk of thermal bridging at the top of the external wall, which is identified by the arrows showing the direction of heat flow in Figure 35.

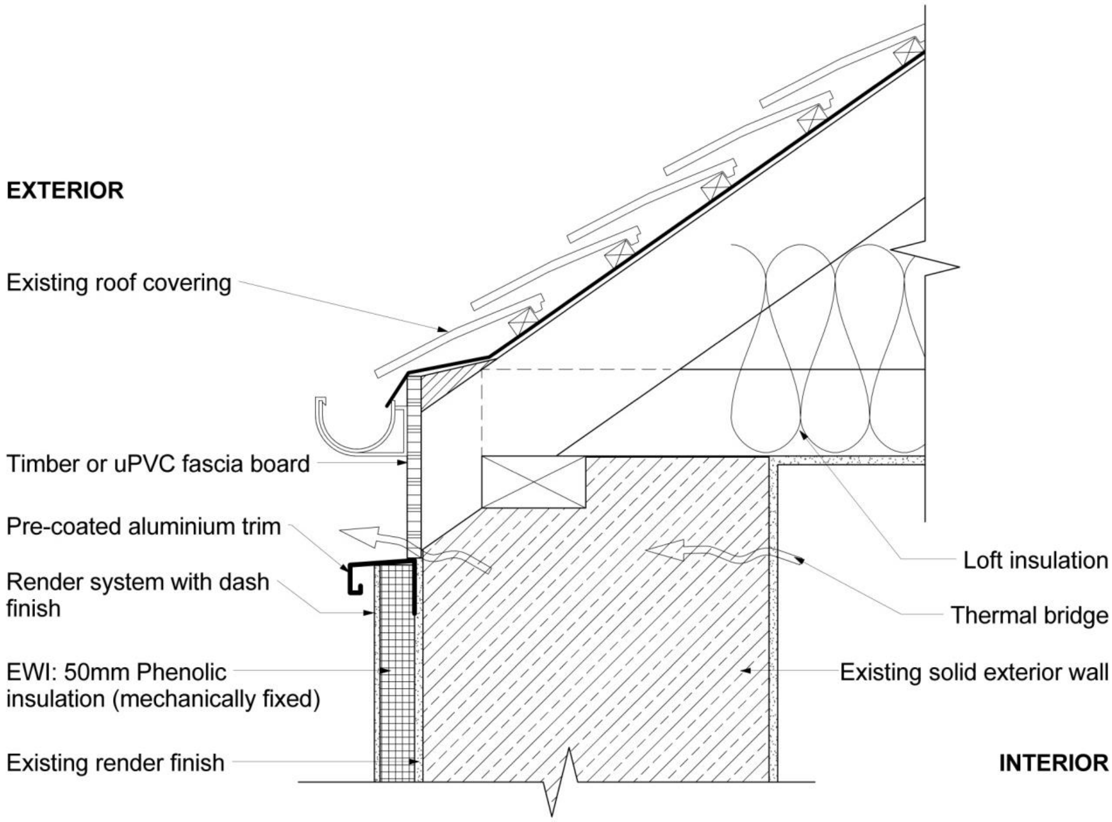


**Figure 35: Eaves junction detail as observed on site**

Figure 36 illustrates the reveals detail, which was observed on site at all the case study dwellings. The EWI was not returned into the reveals of openings and therefore this significant area was not insulated. Only a new surface finish of render was applied to the reveals. This detail was used regardless of the width of window and door frames, even where new windows had been installed immediately prior to the EWI being installed. Unfortunately, in the case of the latter the imminent installation of the EWI was not considered when the new windows were measured for and thus installed.

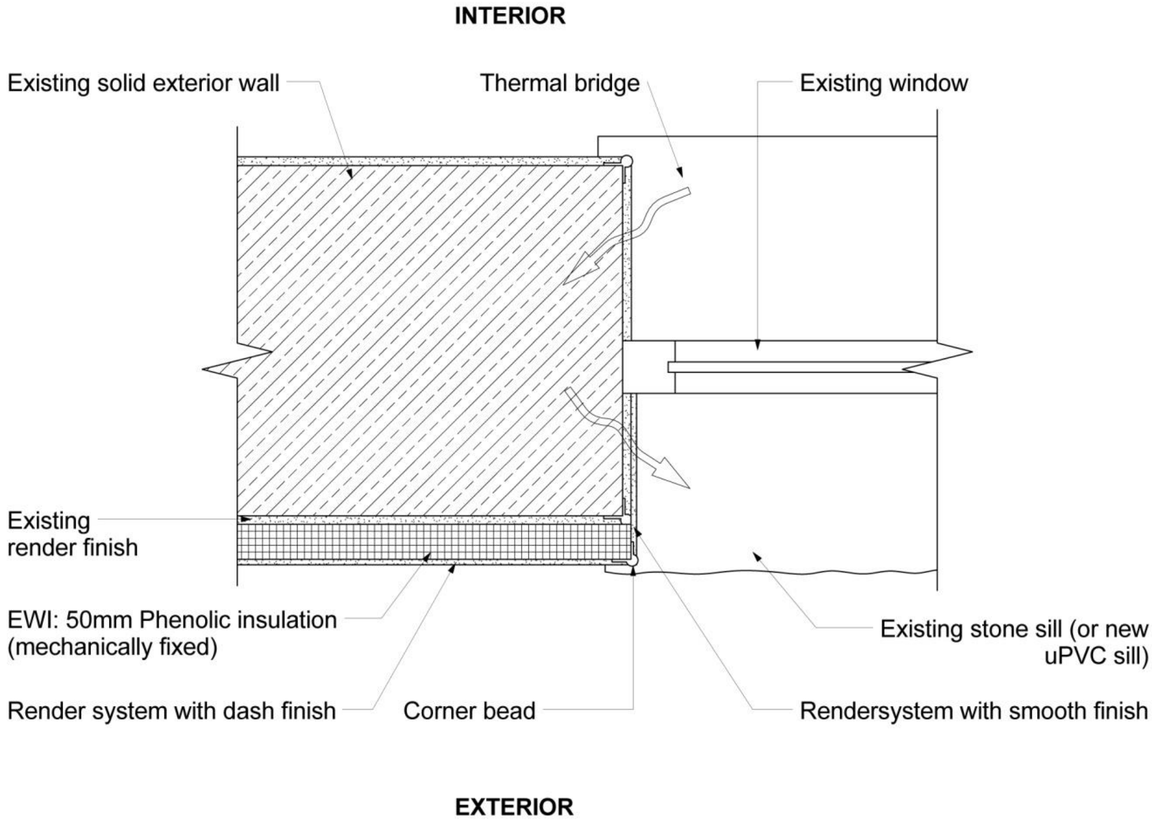


**Figure 36: Reveals detail as observed on site**

Figure 37 illustrates the window sill detail that was adopted by one of the housing associations who provided case study dwellings for this doctoral research project. This approach resulted in the existing stone sill having EWI fixed to the front to maintain the projection from the external wall. The rationale for this approach was based on aesthetics and not thermal performance. As a result, a thermal bridge was created above and below the sill, as illustrated in Figure 37. However, this detail is not consistent with the details provided by the manufacturer, as shown in Figures 4 and 5 in Appendix XIV. The details shown in Figures 4 and 5 illustrates that the manufacturer recommended that a capping profile was used to protect the top of the EWI, which is either located on top or under the sill, as used at the eaves and verge, which is illustrated in Figures 35 above.

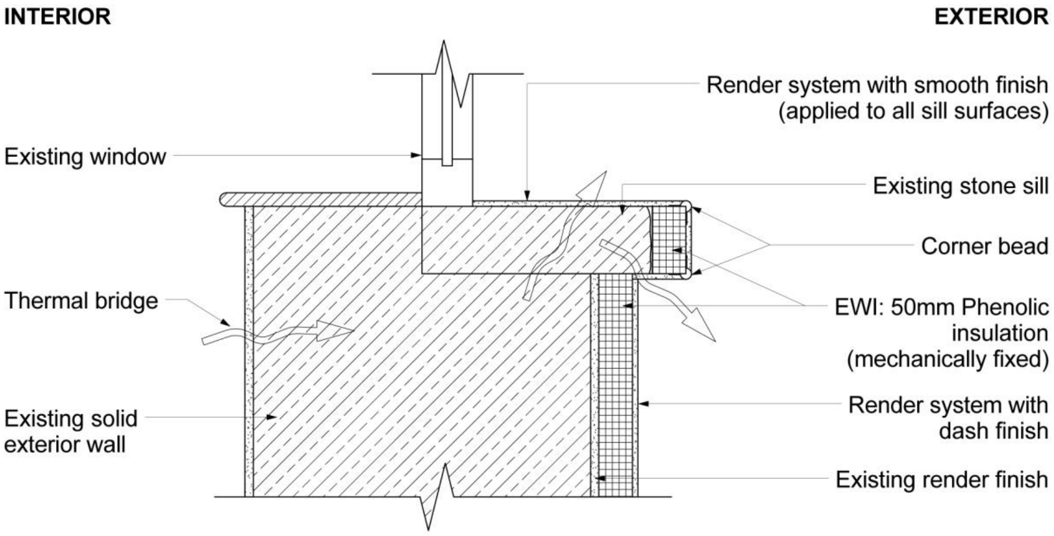


**Figure 37: Window sill detail (1 of 2) as observed on site**

Figure 38 illustrates the window sill detail that was adopted by the other housing association which provided case study dwellings for this doctoral research project. This approach resulted in the overhang of the stone sill being cut off flush with the external wall and a UPVC sill being installed. The rationale for this approach was to reduce thermal bridging at this junction. However, as illustrated in Figure 38, it is anticipated that there will still be a thermal bridge through the top of the sill.

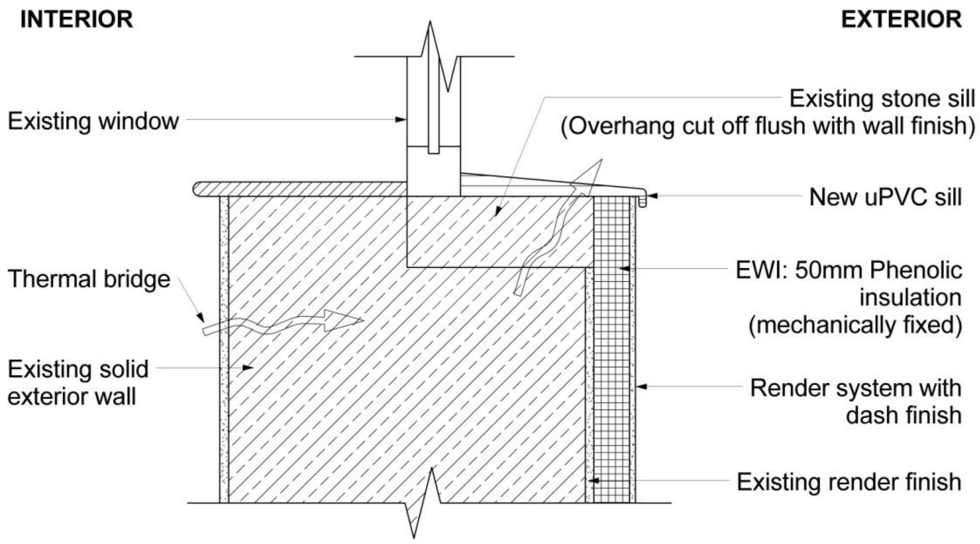


**Figure 38: Window sill detail (2 of 2) as observed on site**

Figure 39 illustrates the technical solution employed at the pavement to external wall junction at all the Arbed I case study dwellings. This detail illustrates that XPS EWI was used at the plinth of the external wall and Phenolic EWI was used above. The rationale for this detail is to reduce the likelihood of water being absorbed by the EWI from the pavement through capillary action. As XPS EWI does not absorb water, the thermal performance is not affected, as is the case with Phenolic EWI. However, due to the location of the internal ground floor level of the case study dwellings and the fact that many are on sloping sites, there is an opportunity for thermal bridging to occur, as illustrated in Figure 39 below.

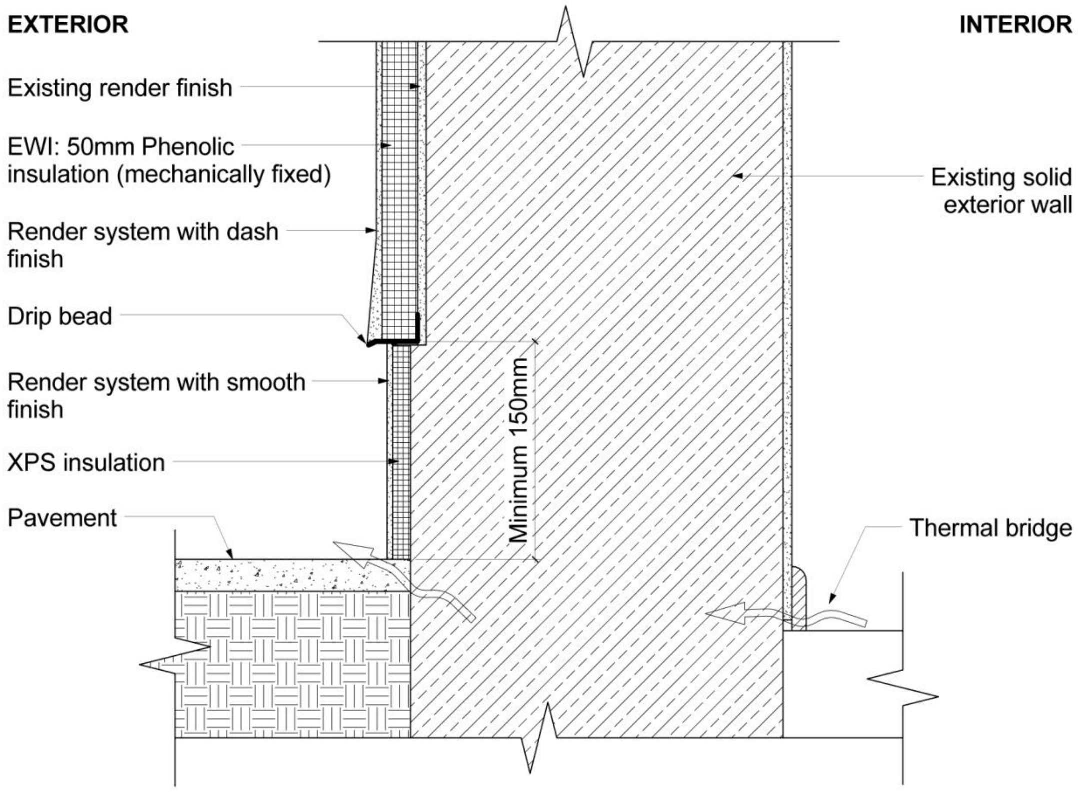


**Figure 39: Pavement to wall junction detail as observed on site**

### 5.2.3 Thermographic surveys

The third set of data for assessing the construction quality of the retrofitted EWI is pre-retrofit and post-retrofit thermographic surveys. The thermal images were collected during qualitative thermographic surveys aimed at assessing overall heat loss, as well as identify any potential thermal bridging, which have been induced as a result of the method of installation and/ or execution quality on site. In particular, the detailed thermographic images provide a method of verifying the potential thermal bridges that were identified as part of producing the observed technical details, as documented in 5.2.2 above. Each of the seven dwellings has been labelled as a case study, commencing with Case Study A and concluding with Case Study G. Case studies A to C were part of a whole street approach to the retrofitted EWI installations. At the window sills of these three case study dwellings, the detail illustrated in Figure 37 in section 5.2.2 above was implemented. Case studies D and E were part of an isolated (or ‘pepper pot’) installation approach, where individual dwellings were retrofitted and thus not part of a whole street approach. At the window sills of these two case study dwellings, the detail illustrated in Figure 38 in section 5.2.2 above was implemented. Case Studies F and G had the same approach as Case Studies A to C. However, the post-retrofit thermographic surveys had to be undertaken in the summer months, which had an impact on the results. Nevertheless, the results are considered, by the author of this thesis, to be important so they have been included at the end of this section.

For each thermographic survey set out, the details and environmental conditions recorded at the time, as well as the meteorological data obtained from the local weather station are set out. The environmental data was recorded at the time of surveys using a Kestrel 3000 weather meter, which was purchased for this doctoral research project. However, for two of the post-retrofit thermographic surveys, it was not possible to record the internal air temperature using the Kestrel 3000 weather meter due to the time that the survey was undertaken. To overcome this issue, the solution implemented was to install ‘Signatrol’ data loggers to record the internal air temperature at 10 minute intervals. Each dwelling had two data loggers installed (one at ground floor level and one at first floor level) within rooms located at the front of the dwellings, prior to the survey. The data loggers were then collected following the surveys. The data was retrieved from the loggers by connecting them to a computer and downloaded using the accompanying ‘TempIT-Pro’ software. The meteorological data that was obtained for these thermographic surveys was downloaded from the City and

County of Swansea (2011; 2013), which was recorded at the Cwm Level Park 30m mast.

Where there was a difference between the external temperatures recorded on the Kestrel 3000 weather meter and from the Cwm Level Park 30m mast, the average ambient air temperature has been used for the purpose of thermally tuning the thermograms. In addition, for some of the thermograms the temperature scale has been set outside the recommended parameters when undertaking the task of thermally tuning these thermal images. This is due to the thermograms not displaying a clear image when set to the standard parameters during this aspect of the analysis process. As discussed in Section 4.3.3 above, the recommended parameters are for the bottom of the temperature scale to be set to 5°C below the ambient air temperature recorded at the time of the survey and the top of the scale to be set at 10-15°C above this lowest temperature; this is to ensure that the ambient air temperature is represented within the range of the green colours in the thermogram.

However, where the bottom of the temperature scale has had to be set lower than 5°C below the ambient air temperature, the top of the scale has been adjusted to ensure that the ambient air temperature recorded at the time of the survey is always represented as a green colour. The rationale for this decision is to ensure that there is consistency with the illustration of all the thermograms. This is considered by the author of this thesis to be of paramount importance for ensuring the quality of this qualitative data due to the comparisons being made between pre-retrofit and post-retrofit surveys.

### *Case Study A*

The pre-retrofit thermographic survey of Case Study A was undertaken on the 17th February 2011, which commenced at 19:30 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 31 and 32, respectively.

**Table 30: Environmental data recorded at the time of the pre-retrofit survey of Case Study A**

| | |
|---|---|
| **Internal temperature** | 24°C |
| **External temperature** | 11.3°C |
| **Wind speed** | 1.5 m/s |

**Table 31: Meteorological data for the pre-retrofit survey of Case Study A (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 6.41°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 11.8°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 5.62°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 0.64 m/s |

Figures 40 and 41 are the pre-retrofit photograph and thermogram, respectively, of Case Study A. The photograph in Figure 39 was taken during the day prior to the thermographic survey. Whilst thermally tuning the thermogram in Figure 41, the bottom of the temperature scale had to be set to -1°C, despite an external temperature of 11.3°C being recorded on the Kestrel 3000 weather meter and 6.41°C at the Cwm Level Park 30m mast. The rationale for setting the bottom of the temperature scale at -1°C is that when it was set to either 6.3°C or 1.41°C the thermogram went completely black and thus no thermal patterns could be seen.

The top of the temperature scale has been set to 19°C, which is 20°C above the bottom of the scale to ensure that the average ambient air temperature at the time of the survey would be represented as green in the thermogram. For the purpose of analysing the results of this thermographic survey, the average ambient air temperature at the time of the survey has been taken as 8.7°C, which is the average of 11.3°C and 6.41°C. The thermogram in Figure 41 appears to confirm that the occupants do not heat the first floor of their dwelling. This is apparent with the warmer areas shown as the intense blue and turquoise colours, either side of the ground floor window and through the window itself compared to the first floor.

Figure 40: Case Study A Pre-retrofit photograph

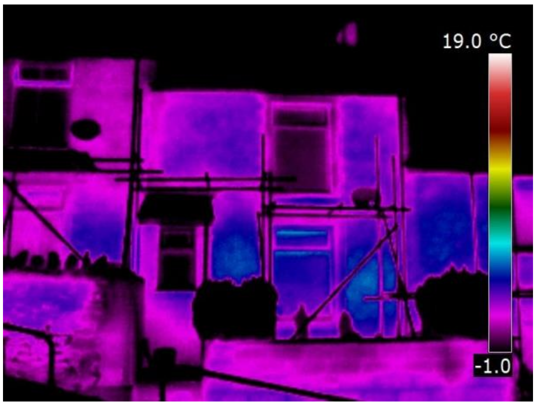


Figure 41: Case Study A Pre-retrofit thermogram

The post-retrofit thermographic survey of Case Study A was undertaken on the 1st March 2012, which commenced at 20:10 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 33 and 34, respectively.

Table 32: Environmental data recorded at the time of the post-retrofit survey of Case Study A

| | |
|---|---|
| **Internal temperature** | 23.6°C |
| **External temperature** | 8°C |
| **Wind speed** | 1.1 m/s |

**Table 33: Meteorological data for the post-retrofit survey of Case Study A (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 7.5°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 12°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 4.8°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 0.9 m/s |

Figures 42 to 49 are the post-retrofit photographs and thermograms of Case Study A. The photographs in Figures 42 and 44 were taken during the day prior to the thermographic survey. Whist thermally tuning the thermograms in Figures 43 and 45 to 49, the bottom of the temperature scale had to be set to -2.0°C and the top to 18°C to ensure there was a visible image and that the ambient air temperature is represented as green in the thermograms. The thermogram in Figure 43 is of the whole facade to illustrate a direct comparison with Figure 41 above. Overall there appears to be a reduction in heat loss through the external walls, which is illustrate by the black areas of this thermal element in the thermogram.

However, there appears to be inconsistency with this heat loss. Between the ground floor window and the porch, as well as a narrow area to the right of the ground floor window, there appears to be more heat loss than through the rest of the external wall. The latter narrow area is consistent with the occupants claim that water is penetrating the EWI after pooling on the first floor window sill. In addition, the area of the external wall below and to the right of the porch window there appears to be less of a reduction in heat loss. These areas of the external wall are illustrated as purple colour in the thermogram. Furthermore, at the reveals and under the window sill there appears to be significant areas of heat loss, which is consistent with these areas having not been covered with EWI and therefore where thermal bridging has occurred, as discussed in sections 5.2.1 and 5.2.2 above.

**Figure 42: Case Study A Post-retrofit photograph – whole facade**

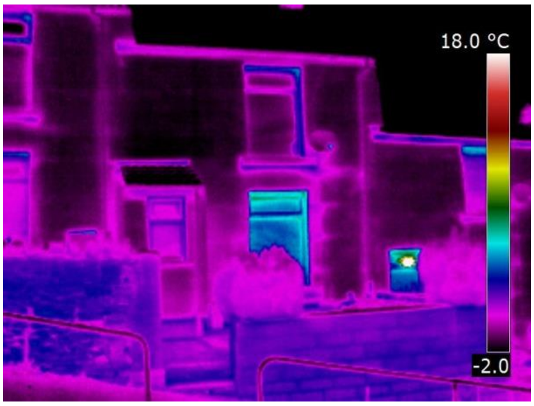


**Figure 43: Case study A Post-retrofit thermogram – whole facade**

Figures 44 and 45 are a photograph and thermogram of the bottom of the first floor window and the top of the ground floor window, which also illustrates part of the narrow area identified above where there appears to be less of a reduction in heat loss through the external wall, as well as the area where the occupant claims water is penetrating the EWI. The area of increased heat loss is consistent with an increase in thermal conductivity, which would result from this area being wet. The pattern is also consistent with the water travelling and thus spreading between the EWI boards. In addition, the un-insulated areas below the first floor window sill and the head of the ground floor window, illustrated as green, turquoise and blue colours in the thermogram, are distinctly apparent and consistent with the thermal bridging identified in sections 5.2.1 and 5.2.2 above.

Figure 44: Case Study A Post-retrofit photograph of bottom of first floor window and top of ground floor window

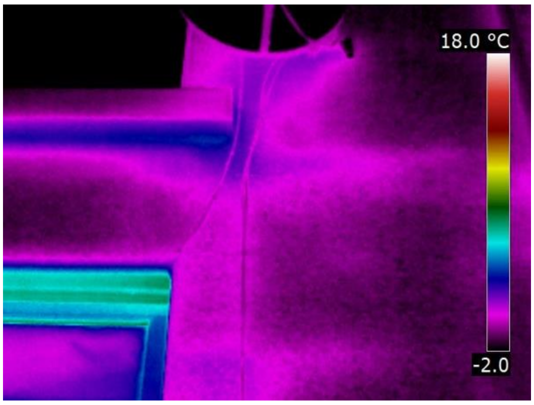


Figure 45: Case study A Post-retrofit thermogram of bottom of first floor window and top of ground floor window

Figures 46 and 47 are thermograms of the top and bottom of the ground floor window. In Figure 46 the significant difference in heat loss between the external wall, which has received EWI and the window reveal that has not been insulated, is clearly visible and illustrated by the green, turquoise and blue colours in the thermogram. Figure 47 illustrates the top of the window sill and part of the reveal of the ground floor window. The dark blue area on top of the window sill and turquoise area at the reveal is consistent with increased heat loss and thus the thermal bridging that has been created through these areas having not been insulated. In addition, Figure 47 illustrates that there appears to be a reduced thermal performance of the XPS EWI at the plinth of the wall compared to the Phenolic EWI above, which is identifiable by the blue shade of this area in the thermogram.

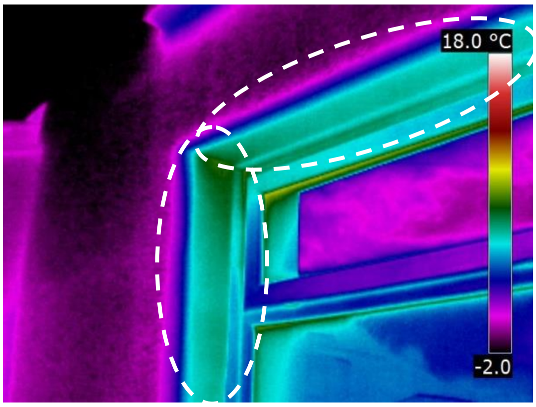


**Figure 46: Case Study A Post-retrofit thermogram of ground floor window head and reveal**

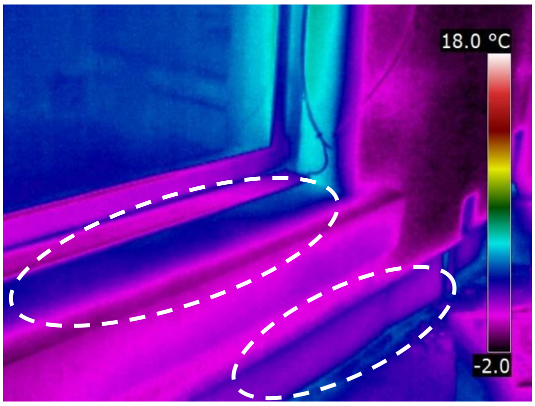


**Figure 47: Case Study A Post-retrofit thermogram of ground floor window sill and reveal**

Figure 48 is a thermogram of the external wall to garden wall junction at Case Study A. The turquoise coloured area at the junction illustrates the thermal bridge that has been created due to the gaps between the EWI and the garden wall. The thermogram in Figure 49 illustrates the heat loss due to the thermal bridge created between the junction of the two EWI materials installed above and at the plinth of the external wall. In addition, the reduced thermal performance of the XPS EWI at the plinth of the wall is clearly visible in the thermogram in Figure 49.

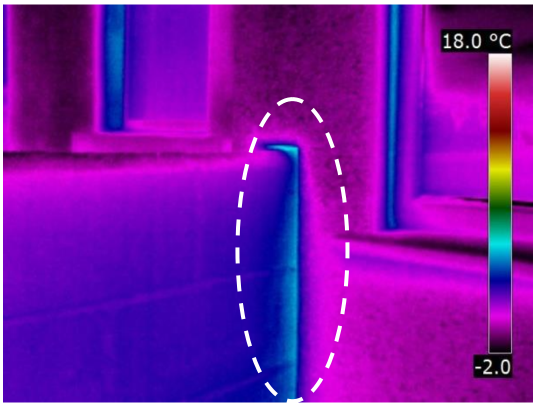


**Figure 48: Case Study A thermogram of external wall to garden wall junction**

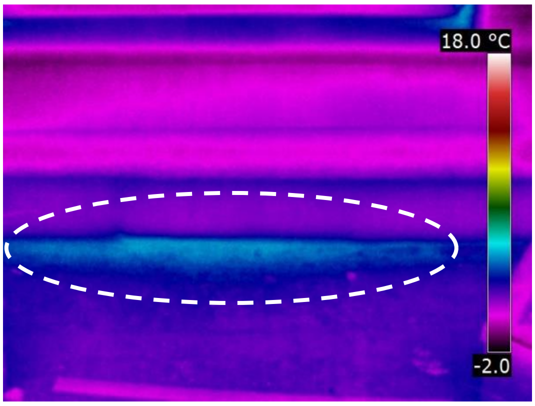


**Figure 49: Case Study A Post-retrofit thermogram of junction between EWI above and at plinth of external wall**

### *Case Study B*

The pre-retrofit thermographic survey of Case Study B was undertaken on the 27th January 2011, which commenced at 18:00 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 35 and 36, respectively.

**Table 34: Environmental data recorded at the time of the pre-retrofit survey of Case Study B**

| | |
|---|---|
| **Internal temperature** | 24.5°C |
| **External temperature** | 3.5°C |
| **Wind speed** | 0.7 m/s |

**Table 35: Meteorological data for the pre-retrofit survey of Case Study B (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 2.95°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 6.15°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 1.45°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 2.64 m/s |

Figures 50 to 53 are the pre-retrofit photographs and thermograms of Case Study B. There are two sets of pre-retrofit photographs and thermograms set out for this case study due to the hedge in the front garden preventing a complete view of the dwelling in one image. The photographs in Figures 50 and 52 were taken during the day prior to the thermographic survey. The thermograms in Figure 51 and 53 appear to indicate that the occupant only heats the ground floor of their dwelling. This is apparent from the warmer areas shown as the intense turquoise colour, either side of the front door and through the ground floor window and the front door itself.

Figure 50: Case Study B Pre-retrofit photograph 1 of 2

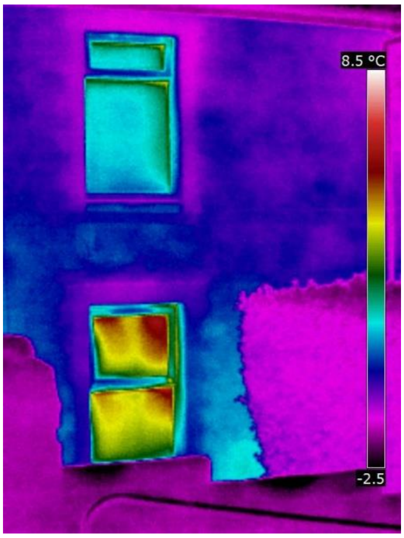


Figure 51: Case Study B Pre-retrofit thermogram 1 of 2

Figure 52: Case Study B Pre-retrofit photograph 2 of 2

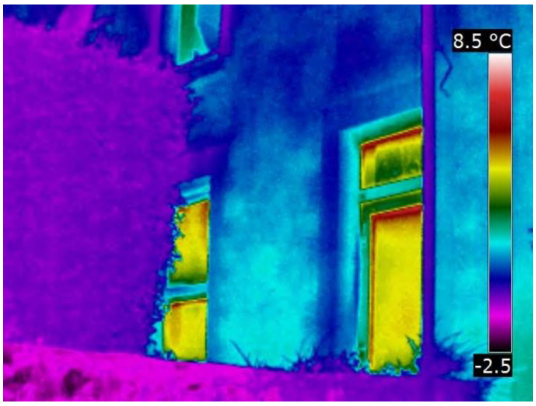


Figure 53: Case Study B Pre-retrofit thermogram 2 of 2

The post-retrofit thermographic survey of Case Study B was undertaken on the 1st March 2012, which commenced at 20:00 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 37 and 38, respectively.

Table 36: Environmental data recorded at the time of the post-retrofit survey of Case Study B

| | |
|---|---|
| **Internal temperature** | 24.4°C |
| **External temperature** | 8°C |
| **Wind speed** | 1.1 m/s |

**Table 37: Meteorological data for the post-retrofit survey of Case Study B (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 7.5°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 12°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 4.8°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 0.9 m/s |

Figures 54 is the post-retrofit photograph of Case Study B and Figures 55 to 59 are the post-retrofit thermograms. The photograph in Figures 54 was taken during the day prior to the thermographic survey. Whist thermally tuning the thermograms in Figures 55 to 59, the bottom of the temperature scale had to be set to -2.0°C and the top to 18°C to ensure there was a visible image and that the ambient air temperature is represented as green in the thermograms. The thermogram in Figure 55 is of the whole facade to illustrate a direct comparison with Figure 51 above. Overall there appears to be a reduction in heat loss through the external walls, which is illustrated by the purple and black areas of this thermal element in the thermogram. However, at the reveals there appears to be significant areas of heat loss, which is consistent with these areas having not been covered with EWI and therefore where thermal bridging has occurred, as discussed in sections 5.2.1 and 5.2.2 above.

Figure 54: Case Study B Post-retrofit photograph – whole facade


Figure 55: Case study B Post-retrofit thermogram – whole facade

Figures 56 and 57 are thermograms of the ground floor window and the top of the front door, respectively. The lack of EWI at the reveals, illustrated as green, turquoise and blue colours in the thermograms, are distinctly apparent and consistent with the thermal bridging identified in sections 5.2.1 and 5.2.2 above. In addition, the reduced thermal performance of the XPS EWI at the plinth of the external wall is evident in Figure 52.

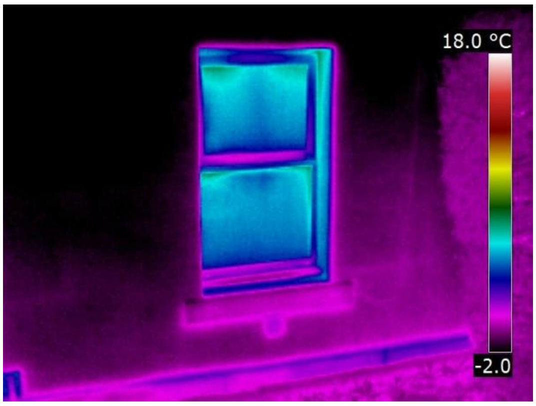


Figure 56: Case Study B Post-retrofit thermogram of ground floor window


Figure 57: Case Study B Post-retrofit thermogram of top of front door

Figures 58 and 59 are thermograms of below the front door and the junction between the garden walls and the external wall of the dwelling, respectively. The area below the front door was not insulated and therefore a thermal bridge has been created, which is evident from the turquoise and blue colours in the thermogram in Figure 58. The gap between the EWI and the garden wall, illustrated as turquoise and green colours in Figure 59, indicates that a thermal bridge has been created.

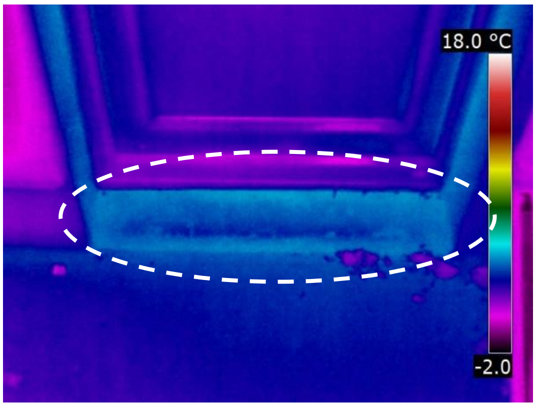


**Figure 58: Case Study B Post-retrofit thermogram of step below front door**

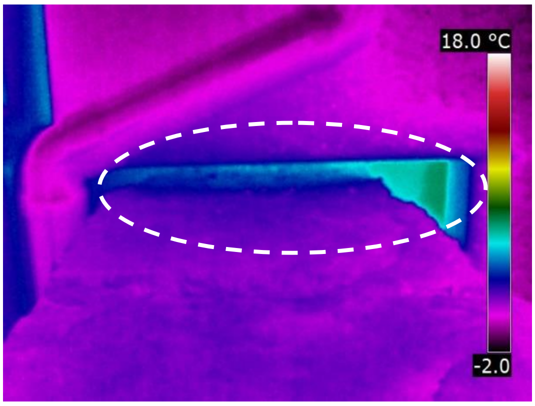


**Figure 59: Case Study B Post-retrofit thermogram of garden wall to external wall junction**

### *Case Study C*

The pre-retrofit thermographic survey of Case Study C was undertaken on the 27th January 2011, which commenced at 19:30 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 39 and 40, respectively.

**Table 38: Environmental data recorded at the time of the pre-retrofit survey of Case Study C**

| | |
|---|---|
| **Internal temperature** | 22.6°C |
| **External temperature** | 3.5°C |
| **Wind speed** | 1.2 m/s |

**Table 39: Meteorological data for the pre-retrofit survey of Case Study C (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 3.05°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 5.16°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 1.45°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 3.95 m/s |

Figures 60 and 61 are the pre-retrofit photograph and thermogram, respectively, of Case Study C. The photograph in Figure 60 was taken during the day prior to the thermographic survey. The thermogram illustrated in Figure 61 indicates that there is significant heat loss through the external walls at this dwelling, which appears to be relatively uniform across the facade. Furthermore, the thermogram indicates that the occupant heats the ground floor to a higher temperature than the first floor.

**Figure 60: Case Study C Pre-retrofit photograph**

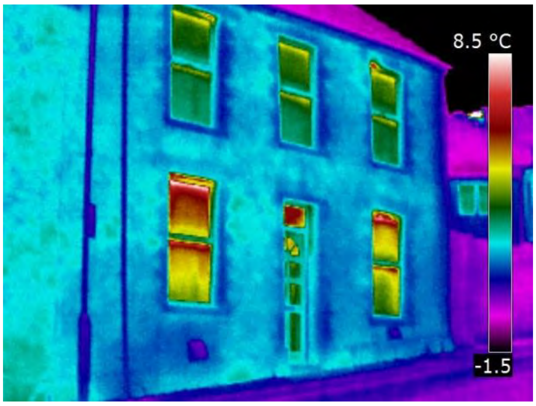


**Figure 61: Case Study C Pre-retrofit thermogram**

The post-retrofit thermographic survey of Case Study C was undertaken on the 1st March 2012, which commenced at 19:30 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 41 and 42, respectively.

**Table 40: Environmental data recorded at the time of the post-retrofit survey of Case Study C**

| | |
|---|---|
| **Internal temperature** | 24.3°C |
| **External temperature** | 8.2°C |
| **Wind speed** | 0.8 m/s |

**Table 41: Meteorological data for the post-retrofit survey of Case Study C (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 8.5°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 12°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 4.8°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 0.9 m/s |

Figure 62 is the post-retrofit photograph and Figures 63 to 67 are the post-retrofit thermograms of Case Study C. The photograph in Figures 62 was taken during the day prior to the thermographic survey. Whist thermally tuning the thermograms in Figures 63 to 67, the bottom of the temperature scale had to be set to 0.7°C and the top to 15.7°C to ensure there was a visible image and that the ambient air temperature is represented as green in the thermograms. The thermogram in Figure 63 is of the whole facade to illustrate a direct comparison with Figure 61 above. Overall there appears to be a reduction in heat loss through the external walls, which is illustrated by the purple areas of this thermal element in the thermogram. However, at the reveals and under the window sill there appears to be significant areas of heat loss, which is consistent with these areas having not been covered with EWI and therefore where thermal bridging has occurred, as discussed in sections 5.2.1 and 5.2.2 above.

Figure 62: Case Study C Post-retrofit photograph – whole facade

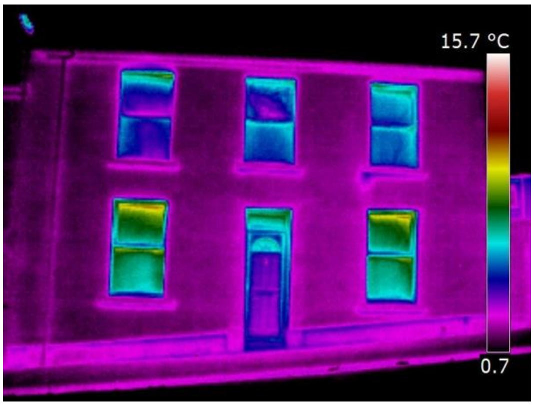


Figure 63: Case study C Post-retrofit thermogram – whole facade

The thermogram in Figure 64 illustrates where the gas and telephone services enter the dwelling at the plinth level of the external walls. Due to the gaps that have been left around these entry points, small areas of thermal bridging has been created, which are illustrated as turquoise colour in the thermogram. Figure 65 is a thermogram of the front door. The blue and turquoise colours around the door frame illustrate the thermal bridging that has been created at the reveals and below the front door.

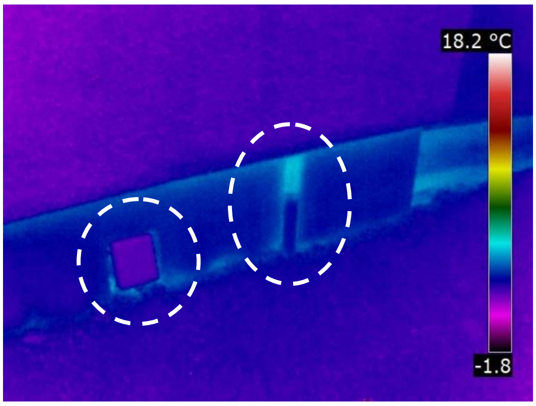


Figure 64: Case Study C Post-retrofit thermogram of services entry

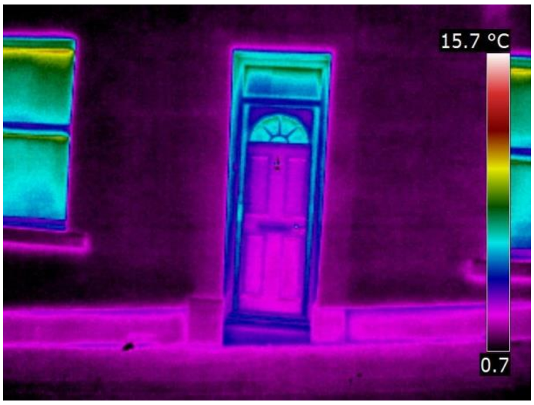


Figure 65: Case Study C Post-retrofit thermogram of front door

Figure 66 is a thermogram of one of the ground floor windows and the plinth level of the external wall below. The thermogram illustrates the thermal bridging that has been created at the reveals, below the window sill and the junctions between the XPS EWI that has been used at the plinth level with both the Phenolic EWI above and the pavement below. The thermal bridging is identifiable by the blue, turquoise, green and yellow colours in these areas shown in the thermograms. In addition, the reduced thermal performance of the XPS EWI at the plinth of the external wall is evident in this thermogram. Figure 67 is a thermogram of two of the first floor windows, as well as the top of the other ground floor window. The thermogram illustrates the thermal bridging that has been created at the reveals and below the window sills. Again, these are identifiable by the thermal patterns displayed in the thermogram, in particular the blue and turquoise colours. These thermal bridges are all consistent with those identified in the photographs and technical details in sections 5.2.1 and 5.2.2 above.

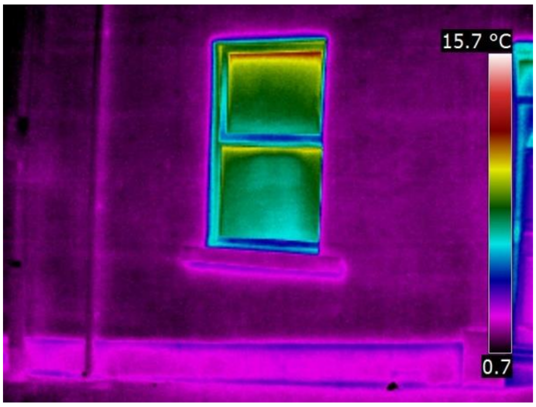


**Figure 66: Case Study C Post-retrofit thermogram of ground floor window**

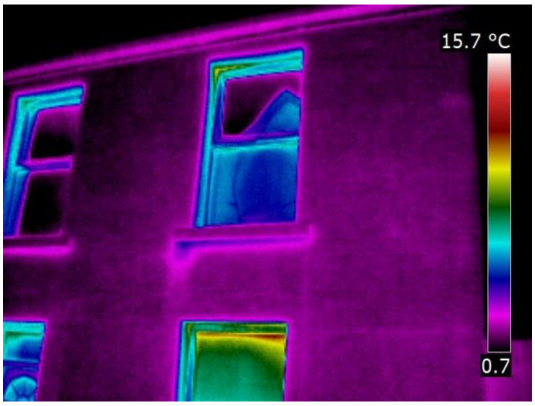


**Figure 67: Case Study C Post-retrofit thermogram of first floor windows**

### *Case Study D*

The pre-retrofit thermographic survey of Case Study D was undertaken on the 7th April 2011, which commenced at 21:30 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 43 and 44, respectively.

Table 42: Environmental data recorded at the time of the pre-retrofit survey of Case Study D

| | |
|---|---|
| **Internal temperature** | 22.7°C |
| **External temperature** | 15.6°C |
| **Wind speed** | 0.5 m/s |

Table 43: Meteorological data for the pre-retrofit survey of Case Study D (City and County of Swansea, 2011)

| | |
|---|---|
| **Average external air temperature during survey** | 15.2°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 17.6°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 8.44°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 0.62 m/s |

Figures 68 and 69 are the pre-retrofit photograph and thermogram, respectively, of Case Study D. The photograph in Figure 68 was taken during the day prior to the thermographic survey. The thermogram in Figure 69 indicates that the heat loss from the external walls at this dwelling is significantly less than through the external walls at the dwellings either side. Without further investigations, it is not possible to determine a rationale for this discrepancy. However, given that the green colour, which is prevalent at the neighbouring dwellings, as well as at the ground floor window and front door surrounds at Case Study D, it is likely that the existing render on the external walls is providing some resistance to heat loss. Furthermore, there also appears to be existing thermal bridging at the reveals of the windows, particularly at ground floor level, and front door, as well as below the first floor window sills. Collectively, it appears that the occupant heats the ground floor more than the first floor.

Figure 68: Case Study D Pre-retrofit photograph

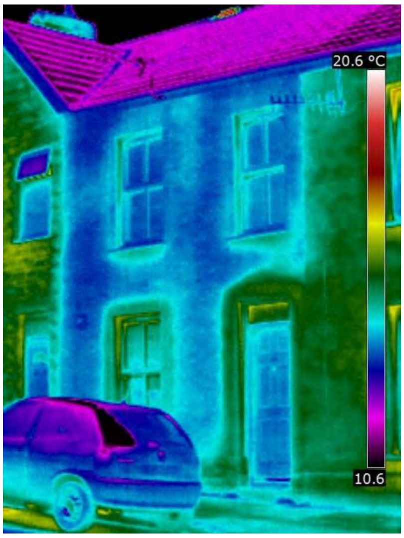


Figure 69: Case Study D Pre-retrofit thermogram

The post-retrofit thermographic survey of Case Study D was undertaken on the 1st March 2012, which commenced at 21:15 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 45 and 46, respectively.

Table 44: Environmental data recorded at the time of the post-retrofit survey of Case Study D

| | |
|---|---|
| **Internal temperature** | 24.4°C |
| **External temperature** | 7.7°C |
| **Wind speed** | 0.0 m/s |

Table 45: Meteorological data for the post-retrofit survey of Case Study D (City and County of Swansea, 2011)

| | |
|---|---|
| **Average external air temperature during survey** | 7.6°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 12°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 4.8°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 0.8 m/s |

Figure 70 is the post-retrofit photograph and Figures 71 to 77 are the post-retrofit thermograms of Case Study D. The photograph in Figure 70 was taken during the day prior to the thermographic survey. Whist thermally tuning the thermograms in Figures 71 to 77, the bottom of the temperature scale had to be set to -2.3°C and the top to 17.7°C to ensure there was a visible image and that the ambient air temperature is represented as green in the thermograms. The thermogram in Figure 71 is of the whole facade to illustrate a direct comparison with Figure 69 above. Overall there appears to be a reduction in heat loss through the external walls, which is illustrated by the black and purple areas of this thermal element in the thermogram. However, there appears to be significant areas of heat loss, which are consistent with some of the thermal bridging identified in sections 5.2.1 and 5.2.2 above.

**Figure 70: Case Study D Post-retrofit photograph – whole facade**


**Figure 71: Case study D Post-retrofit thermogram – whole facade**

Figures 72 and 73 are thermograms of the first floor windows. Both thermograms appear to confirm that thermal bridging at the reveals and head of the window due to EWI having not been installed in these locations, which is evident by the blue, turquoise and green colours. However, there does not appear to be any thermal bridging under the window sill, as evident in the Case Studies A, B and C above. This lack of thermal bridging under the window sill is consistent with the technical detail in Figure 38 in section 5.2.2 above.


**Figure 72: Case Study D Post-retrofit thermogram of the top left first floor window**


**Figure 73: Case study D Post-retrofit thermogram of top right first floor window**

Figures 74 and 75 are thermograms of the ground floor window and front door, respectively. Both thermograms illustrate potential thermal bridging at the reveals, which is illustrated by the blue and turquoise colours. In addition, there appears to be thermal bridging at the junctions between the XPS EWI at the plinth of the external wall and the Phenolic EWI above, as illustrated in Figure 74, as well as between the XPS EWI and the pavement, as illustrated in Figure 75. Both thermal bridges at these junctions are illustrated as blue in the thermograms. However, compared to Case Studies A to C above, there does not appear to be a generally reduced thermal performance at the plinth of external wall.

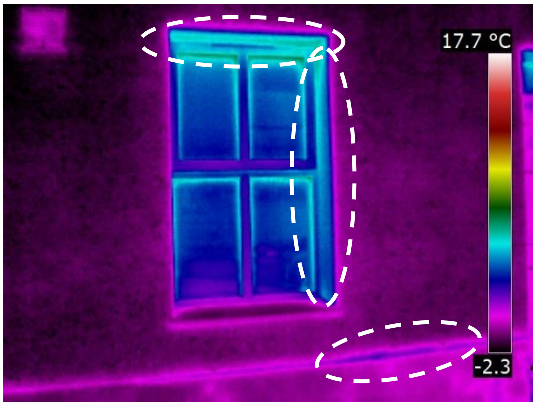


Figure 74: Case Study D Post-retrofit thermogram of the ground floor window

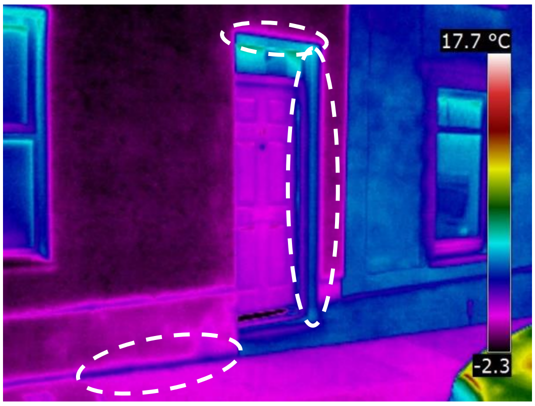


Figure 75: Case Study D Post-retrofit thermogram of the front door

Figure 76 is a thermogram of the plinth of external wall to pavement junction, which also illustrates a service entry point. There appears to be a thermal bridge at the external wall to pavement junction, which is illustrated by the blue colour in this location in the thermogram. In addition, the blue colour around the service entry point indicates that thermal bridging has occurred in this location too. Figure 77 is a thermogram of the step below the front door and the stark blue colour of this area indicates heat loss and thus thermal bridging in this location.

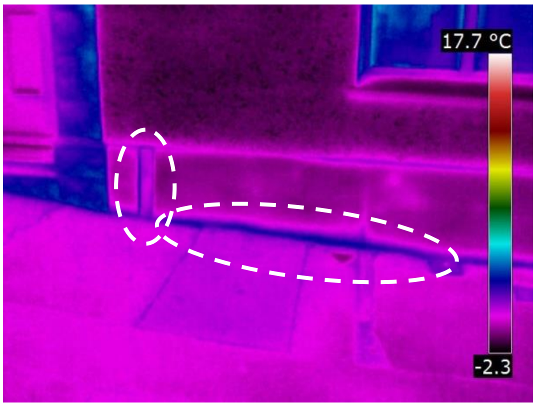


Figure 76: Case Study D thermogram of external wall to pavement junction


Figure 77: Case Study D Post-retrofit thermogram of step below front door

### *Case Study E*

The pre-retrofit thermographic survey of Case Study E was undertaken on the 7$^{th}$ April 2011, which commenced at 21:00 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 47 and 48, respectively.

**Table 46: Environmental data recorded at the time of the pre-retrofit survey of Case Study E**

| | |
|---|---|
| **Internal temperature** | 24°C |
| **External temperature** | 15.3°C |
| **Wind speed** | 0.5 m/s |

**Table 47: Meteorological data for the pre-retrofit survey of Case Study E (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 15.2°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 17.6°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 8.44°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 0.62 m/s |

Figures 78 and 79 are the pre-retrofit photograph and thermogram, respectively, of Case Study E. The photograph in Figure 78 was taken during the day prior to the thermographic survey. The thermogram in Figure 79 indicates that the occupants predominantly heat the ground floor of their dwelling. This is apparent with the warmer areas shown as the intense green, yellow and red colours at the ground floor level. In particular, there appears to be significant heat loss through the plinth of the external wall. Furthermore, it appears that the roof is not insulated as well as the neighbouring dwellings either side of Case Study E.

Figure 78: Case Study E Pre-retrofit photograph

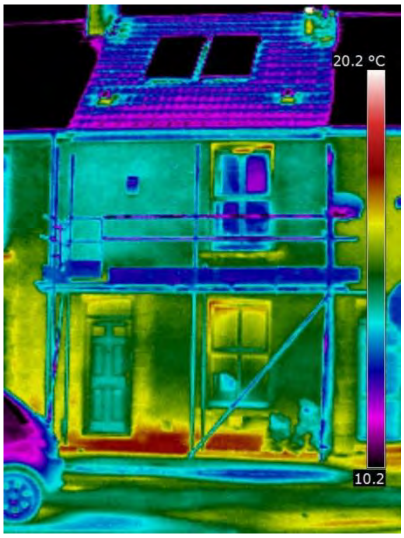


Figure 79: Case Study E Pre-retrofit thermogram

The post-retrofit thermographic survey of Case Study E was undertaken on the 1st March 2012, which commenced at 19:00 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 49 and 50, respectively.

Table 48: Environmental data recorded at the time of the post-retrofit survey of Case Study E

| | |
|---|---|
| **Internal temperature** | 24°C |
| **External temperature** | 11.1°C |
| **Wind speed** | 0 m/s |

Table 49: Meteorological data for the post-retrofit survey of Case Study E (City and County of Swansea, 2011)

| | |
|---|---|
| **Average external air temperature during survey** | 8.5°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 12°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 4.8°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 0.9 m/s |

Figure 80 is the post-retrofit photograph and Figures 81 to 85 are the post-retrofit thermograms of Case Study E. The photograph in Figure 80 was taken during the day prior to the thermographic survey. Whilst thermally tuning the thermograms in Figures 81 to 85, the bottom of the temperature scale had to be set to -0.5°C, despite an external temperature of 11.1°C being recorded on the Kestrel 3000 weather meter and 8.5°C at the Cwm Level Park 30m mast. The rationale for setting the bottom of the temperature scale at -0.5°C is that when it was set to either 6.1°C and 3.5°C the thermogram went completely black and thus no thermal patterns could be seen.

The top of the temperature scale has been set to 19.5°C, which is 20°C above the bottom of the scale to ensure that the average ambient air temperature at the time of the survey would be represented as green in the thermogram. For the purpose of analysing the results of this thermographic survey, the average ambient air temperature at the time of the survey has been taken as 9.5°C, which is the average of 11.1°C and 8.5°C. The thermogram in Figure 84 is of the whole facade to illustrate a direct comparison with Figure 79 above. Overall there appears to be a reduction in heat loss through the external walls, which is illustrated by the purple areas of this thermal element in the thermogram. However, there appears to be significant areas of heat loss, which are consistent with the thermal bridging identified in sections 5.2.1 and 5.2.2 above.

**Figure 80: Case Study E Post-retrofit photograph – whole facade**

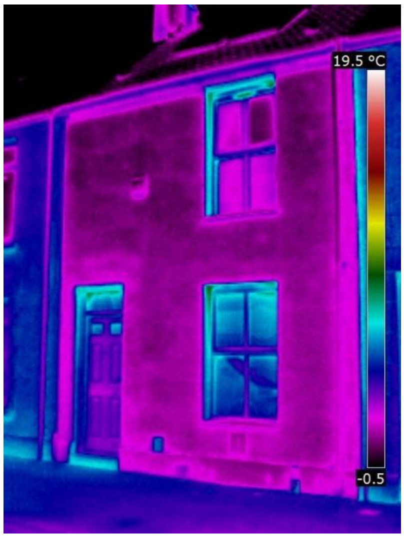


**Figure 81: Case study E Post-retrofit thermogram – whole facade**

Figures 82 and 83 are thermograms of the front door and ground floor window, respectively. Both thermograms indicate that thermal bridging has occurred at the reveals and head of these openings, which are evident by the blue, turquoise and green colours. In addition, there appears to be a thermal bridge at the step below the front door, which is evident by the turquoise colour in the thermogram in Figure 82. However, there does not appear to be a thermal bridge through the top of the window sill shown in Figure 83. As part of the analysis of the technical detail shown in Figure 38 in section 5.2.2 above it was expected that there would be a thermal bridge in this location.

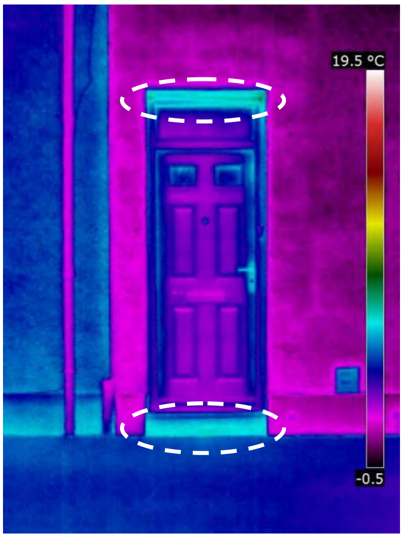


**Figure 82: Case Study E Post-retrofit thermogram of the front door**

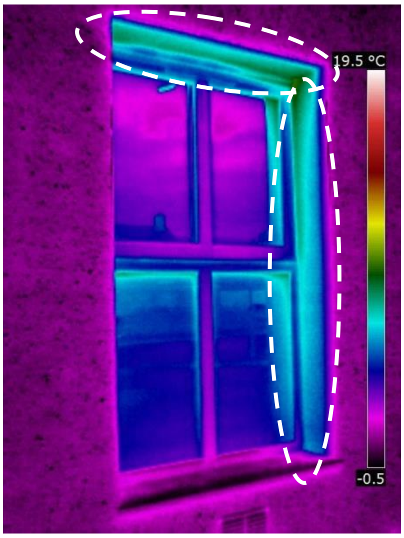


**Figure 83: Case study E Post-retrofit thermogram of the ground floor window**

Figures 84 and 85 are thermograms of the plinth of the external wall. As with Case Study D above, there does not appear to be an overall reduced thermal performance at this location of the external wall. However, there are anomalies, which are illustrated by the blue circular shapes in the thermograms. These anomalies appear to be thermal bridging caused by the fixings for the EWI. Nevertheless, compared to the pre-retrofit thermogram in Figure 79 above, there appears to be a significant reduction in the heat loss through the plinth of the external wall. In addition, the missing EWI around the service entry point shown in Figure 85 appears to have created a thermal bridge in this location. Furthermore, at this case study the EWI thickness at the plinth of the wall appears to be much greater than the Phenolic used above, as well as thicker than the EWI used at the plinth of the wall at Case Studies A to C.

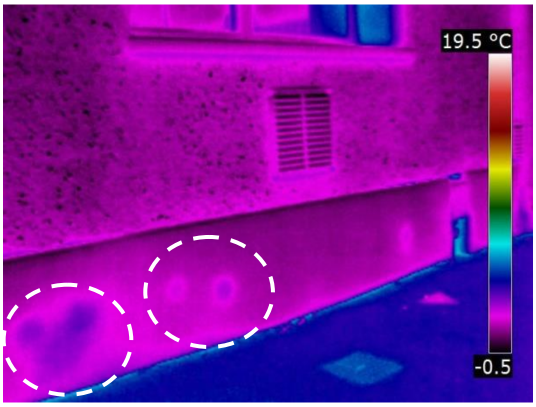


Figure 84: Case Study E Post-retrofit thermogram of the plinth of the external wall

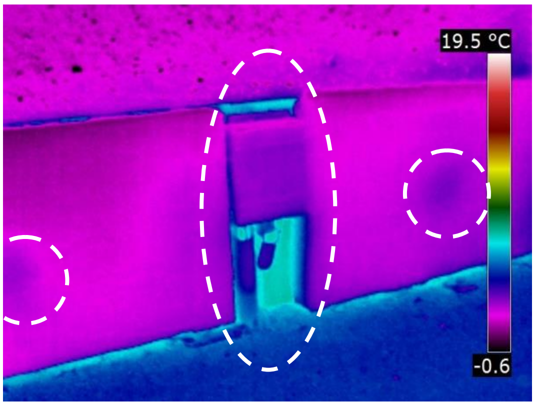


Figure 85: Case Study E Post-retrofit thermogram of a service entry point

### *Case Study F*

The pre-retrofit thermographic survey of Case Study F was undertaken on the 27th January 2011, which commenced at 19:00 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 51 and 52, respectively.

Table 50: Environmental data recorded at the time of the pre-retrofit survey of Case Study F

| | |
|---|---|
| **Internal temperature** | 21.5°C |
| **External temperature** | 4°C |
| **Wind speed** | 1.8 m/s |

Table 51: Meteorological data for the pre-retrofit survey of Case Study F (City and County of Swansea, 2011)

| | |
|---|---|
| **Average external air temperature during survey** | 3.04°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 5.16°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 1.45°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 3.95 m/s |

Figures 86 and 87 are the pre-retrofit photograph and thermogram, respectively, of Case Study F. The photograph in Figure 86 was taken during the day prior to the thermographic survey. The thermogram in Figure 87 appears to illustrate that the heat loss through the external walls is not uniform; the heat loss at ground floor level appears to be greater than at the first floor level. However, it is likely that the internal space in the first floor is cooler than the ground floor due to the first floor window being open.

Figure 86: Case Study F Pre-retrofit photograph

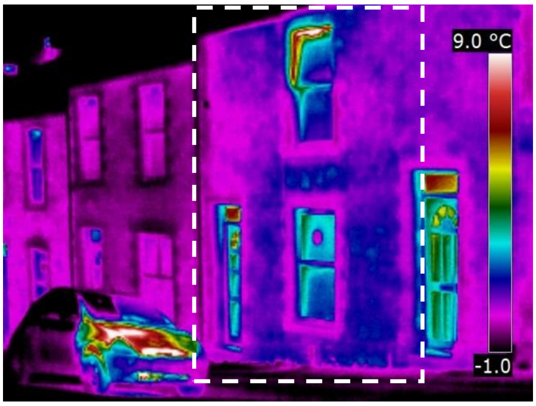


Figure 87: Case Study F Pre-retrofit thermogram

The post-retrofit thermographic survey of Case Study F was undertaken on the 27th June 2011, which commenced at 02:00 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 53 and 54, respectively. As set out in the introduction to this section, the internal temperature was recorded using data loggers due to the time that the survey was undertaken. Due to the time of year, the post-retrofit survey commenced at two hours before sunrise. This time was chosen so as to allow any solar radiation, absorbed by the external walls during the day, to be dispersed as much as possible. Unfortunately, the 26th June 2011 was the warmest day of the year to date and was not ideal for undertaking thermographic surveys. However, the occupants were very cooperative and agreed to activate their heating at 21:00 on the 26th June 2011 and leave it on overnight. They also agreed to keep their windows shut.

**Table 52: Environmental data recorded at the time of the post-retrofit survey of Case Study F**

| | |
|---|---|
| **Internal temperature** | 26.5°C |
| **External temperature** | 19.5°C |
| **Wind speed** | 0.4 m/s |

**Table 53: Meteorological data for the post-retrofit survey of Case Study F (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 16.5°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 27.4°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 14.5°C |
| **Precipitation in 24 hours preceding survey** | 2.6 mm |
| **Average wind speed during survey** | 0.8 m/s |

Figure 88 is the post-retrofit photograph and Figures 88 to 91 are the post-retrofit thermograms of Case Study F. The photograph in Figure 88 was taken during the day prior to the thermographic survey. Whilst thermally tuning the thermogram in Figure 89 to 91, the bottom of the temperature scale was set to 13°C as this is the average temperature between 19.5°C, which was recorded on the Kestrel 3000 weather meter, and 16.5°C recorded at the Cwm Level Park 30m mast. Due to the time of year when this thermographic survey was undertaken, the colours displayed in the thermogram are affected. However, the variation in the colours does not affect the thermal patterns illustrating where potential thermal bridging has occurred. The main impact is that it is difficult to make a direct comparison between the pre-retrofit and post-retrofit thermograms of the whole facade.

The thermogram in Figure 89 is of the whole facade, which should illustrate a direct comparison with Figure 87 above. Whilst it appears that there is more heat loss through the external walls after the EWI has been installed, there has actually been a reduction in overall heat loss. Had there not been a reduction in heat loss, the post-retrofit thermograms would be predominantly green and yellow colours. Nevertheless, this is not obvious when compared to the pre-retrofit thermogram in Figure 87 above. However, there appears to be significant areas of heat loss, which are consistent with the thermal bridging identified in sections 5.2.1 and 5.2.2 above.

**Figure 88: Case Study F Post-retrofit photograph – whole facade**

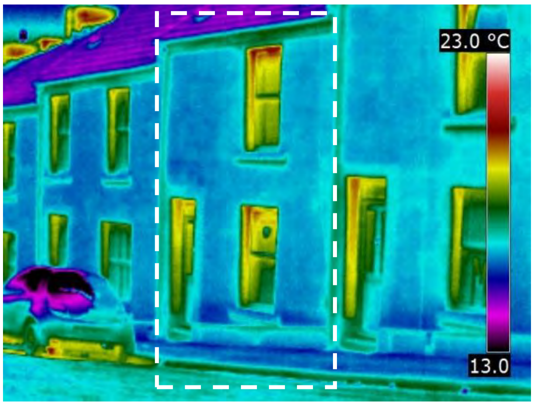


**Figure 89: Case study F Post-retrofit thermogram – whole facade**

Figures 90 illustrates the bottom of the front door and ground floor window, as well as the junction between the XPS EWI at the plinth of the external wall to Phenolic EWI above and the pavement below. At the front door, there appears to be thermal bridging at the reveal and the step below, which is illustrated by the turquoise, green and yellow colours in the thermogram. At the ground floor window the reveal is coloured green and yellow colours, indicating that there is a thermal bridge in this location. The turquoise and green colours under the ground floor window sill and between the EWI at the plinth of the external wall above indicate thermal bridging has occurred. Figure 91 illustrates the first floor window and indicates quite significant thermal bridging at the head, reveal and under the window sill, which is identified by the green, yellow and red colours in the thermogram.

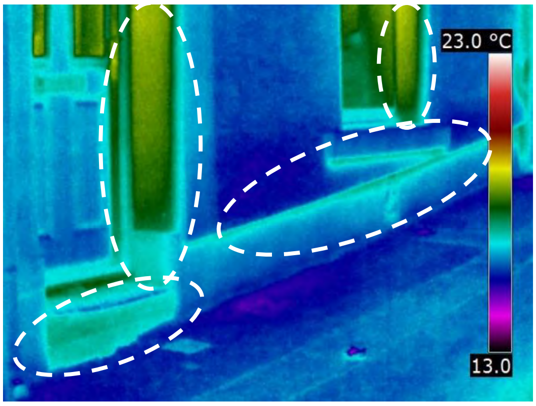


Figure 90: Case Study F Post-retrofit thermogram of bottom of front door and ground floor window

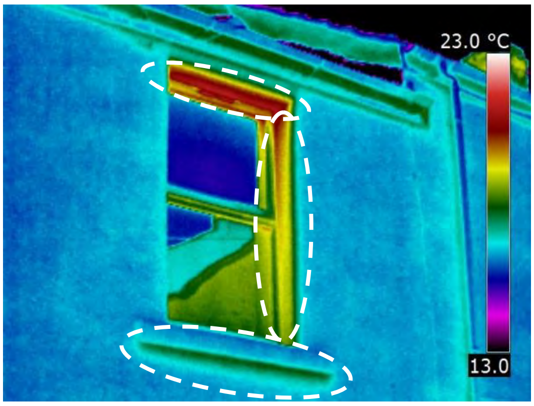


Figure 91: Case study F Post-retrofit thermogram of first floor window

## *Case Study G*

The pre-retrofit thermographic survey of Case Study G was undertaken on the 17th February 2011, which commenced at 20:05 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 55 and 56, respectively.

Table 54: Environmental data recorded at the time of the pre-retrofit survey of Case Study G

| | |
|---|---|
| **Internal temperature** | 23.1°C |
| **External temperature** | 9.8°C |
| **Wind speed** | 0.8 m/s |

**Table 55: Meteorological data for the pre-retrofit survey of Case Study G (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 6.64°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 11.8°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 5.62°C |
| **Precipitation in 24 hours preceding survey** | 0.0 mm |
| **Average wind speed during survey** | 1.14 m/s |

Figures 92 and 93 are the pre-retrofit photograph and thermogram, respectively, of Case Study G. The photograph in Figure 92 was taken during the day prior to the thermographic survey. Whilst thermally tuning the thermogram in Figures 93 to 99, the bottom of the temperature scale had to be set to -1.8°C, despite an external temperature of 9.8°C being recorded on the Kestrel 3000 weather meter and 6.64°C at the Cwm Level Park 30m mast. The rationale for setting the bottom of the temperature scale at -1.8°C is that when it was set to either 4.8°C and 1.6°C the majority of the thermogram went completely black and thus very little thermal patterns could be seen.

The top of the temperature scale has been set to 18.2°C, which is 20°C above the bottom of the scale to ensure that the average ambient air temperature at the time of the survey would be represented as green in the thermogram. For the purpose of analysing the results of this thermographic survey, the average ambient air temperature at the time of the survey has been taken as 8.2°C, which is the average of 9.8°C and 6.6°C. The thermogram in Figure 93 appears to confirm that the occupants only heat the one half of the ground floor, which is on the right in the thermogram. This is apparent with the warmer areas shown as the intense blue and turquoise colours in these areas.

Figure 92: Case Study G Pre-retrofit photograph


Figure 93: Case Study G Pre-retrofit thermogram

The post-retrofit thermographic survey of Case Study G was undertaken on the 27th June 2012, which commenced at 02:25 hours. The environmental data recorded at the time of the survey and the meteorological data are set out in Tables 57 and 58, respectively. As with Case Study F above and set out in the introduction to this section, the internal temperature was recorded using data loggers due to the time that the survey was undertaken. Due to the time of year, the post-retrofit survey commenced at least two hours before sunrise. This time was chosen so as to allow any solar radiation, absorbed by the external walls during the day, to be dispersed as much as possible. Unfortunately, the 26th June 2011 was the warmest day of the year to date and was not ideal for undertaking thermographic surveys. However, the occupants were very cooperative and agreed to activate their heating at 21:00 on the 26th June 2011 and leave it on overnight. They also agreed to keep their windows shut.

Table 56: Environmental data recorded at the time of the post-retrofit survey of Case Study G

| | |
|---|---|
| **Internal temperature** | 26°C |
| **External temperature** | 19.5°C |
| **Wind speed** | 0.4 m/s |

**Table 57: Meteorological data for the post-retrofit survey of Case Study G (City and County of Swansea, 2011)**

| | |
|---|---|
| **Average external air temperature during survey** | 16.5°C |
| **Maximum (hourly average) temperature in 24 hours preceding survey** | 27.4°C |
| **Minimum (hourly average) temperature in 24 hours preceding survey** | 14.5°C |
| **Precipitation in 24 hours preceding survey** | 2.6 mm |
| **Average wind speed during survey** | 0.8 m/s |

Figure 94 is the post-retrofit photograph and Figures 95 to 99 are the post-retrofit thermograms of Case Study G. The photograph in Figure 94 was taken during the day prior to the thermographic survey. As with Case Study F above, whilst thermally tuning the thermograms in Figure 95 to 99, the bottom of the temperature scale was set to 13°C as this is the average temperature between 19.5°C, which was recorded on the Kestrel 3000 weather meter, and 16.5°C recorded at the Cwm Level Park 30m mast. Due to the time of year when this thermographic survey was undertaken, the colours displayed in the thermogram are affected. However, the variation in the colours does not affect the thermal patterns illustrating where potential thermal bridging has occurred. The main impact is that it is difficult to make a direct comparison between the pre-retrofit and post-retrofit thermograms of the whole facade.

The thermogram in Figure 95 is of the whole facade, which should illustrate a direct comparison with Figure 93 above. Whilst it appears that there is more heat loss through the external walls after the EWI has been installed, there has actually been a reduction in overall heat loss. Had there not been a reduction in heat loss, the post-retrofit thermograms would be predominantly green and yellow colours. With this case study, this is evidenced by the garage wall which can be seen in the very left side of the thermogram in Figure 95. Nevertheless, this is not obvious when compared to the pre-retrofit thermogram in Figure 93 above.

**Figure 94: Case Study G Post-retrofit photograph – whole facade**

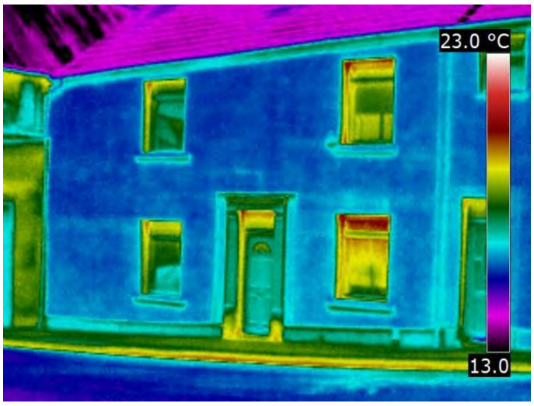


**Figure 95: Case study G Post-retrofit thermogram – whole facade**

Figure 96 is a thermogram of one of the ground floor windows. This thermogram appears to illustrate thermal bridging at the head of the window, evidenced by the yellow and red colours, and below the window sill, which is green in colour. Figure 97 is a thermogram of the front door and appears to illustrate thermal bridging at the reveal and head of the opening; this is evidenced by the yellow and red colours. Furthermore both thermograms indicate that thermal bridging has occurred at the junction between the XPS EWI at the plinth of the external wall and the Phenolic above, as well as with the pavement below. These thermal bridges are consistent with the technical details illustrated in section 5.2.2 above.

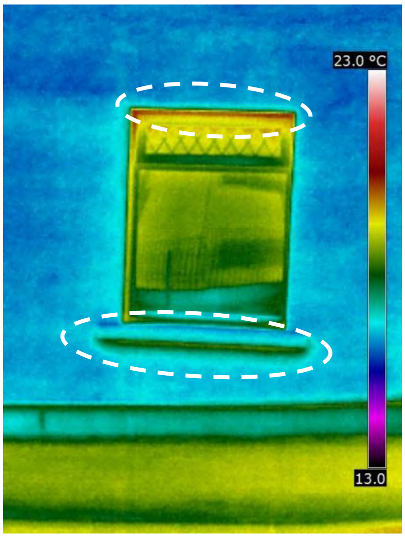


Figure 96: Case Study G Post-retrofit thermogram of one of the ground floor windows

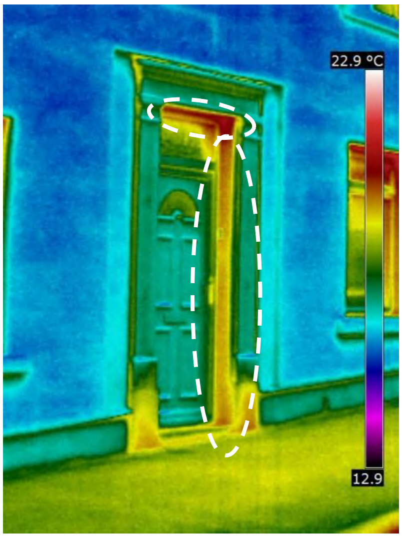


Figure 97: Case study G Post-retrofit thermogram of the front door

Figures 98 and 99 are thermograms of two of the first floor windows. Both thermograms illustrate potential thermal bridging at the reveals, which are illustrated by the yellow and red colours, and under the window sills illustrated by the green colour.

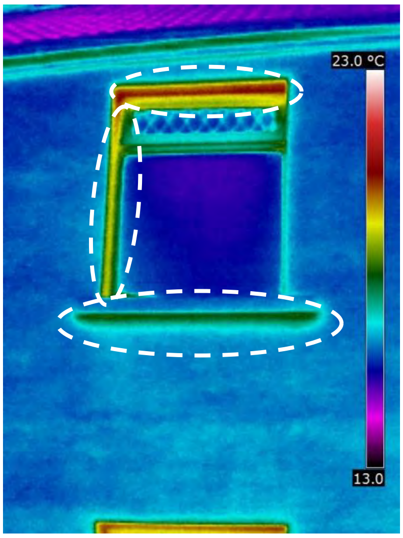


Figure 98: Case Study G Post-retrofit thermogram of one of the first floor windows

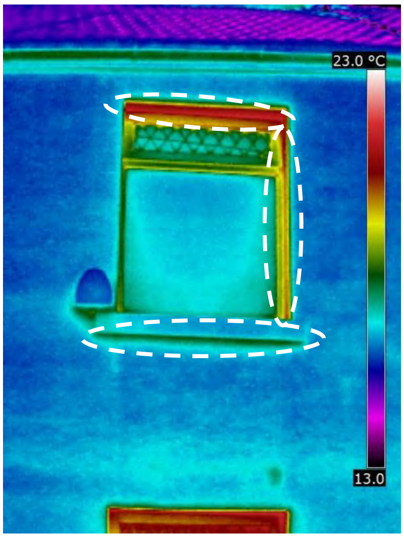


Figure 99: Case Study G Post-retrofit thermogram of another first floor window

## 5.3 Energy performance

This final section of the results presents the quantitative data, which was gathered to assess the energy performance of the retrofitted EWI. The three sets of quantitative data was obtained through: occupant surveys to record post-retrofit thermal comfort perceptions and behaviour, set out in section 5.3.1; energy consumption monitoring to ascertain pre-retrofit and post-retrofit energy usage and carbon emissions, set out in section 5.3.2; and cost-effectiveness calculations to establish the financial benefits of the retrofitted EWI, set out in section 5.3.3.

### 5.3.1 Post-retrofit occupant thermal comfort perceptions and behaviour

One aspect of the post-retrofit occupant surveys focused upon thermal comfort and behaviour data and this was collected from 24 case study dwellings, which represented 10% of the two housing associations' Arbed I dwellings. As part of both the full and short post-retrofit occupant surveys, each occupant was asked two questions about their thermal comfort and behaviour since having the retrofitted EWI installed. These two questions were:

1. Do you feel that your home is warmer since it has been insulated?
2. Have you increased the internal temperature that you keep your home at during the heating season (winter) since having the external wall insulation installed?

To answer the first question, occupants were given three choices: yes; no; or don't know. To answer the second question, the occupants were given the same three options (yes, no and don't know). In addition, there were two sub-questions which followed on from the answer of question two. For these sub-questions, occupants were given the option to select more than one response. The two sub-questions were:

1. If yes, why is this?
2. Because it is easier to do so.
3. Because you need to for health reasons.
4. Because it does not cost any more that before the insulation was installed.
5. Because you like it warmer but couldn’t afford to before you had the insulation installed.
6. Other reason, please specify.
7. If no, why is this?
8. Because you are trying to save money on your heating bill.
9. Because it does not feel as cold inside (even when the external temperature is particularly low).
10. Other reason, please specify.

From the 24 case study dwellings, the range of answers given to question one above is set out in the pie chart in Figure 100 below. As can be seen from the pie chart, occupants at 71% of the case study dwellings, which represents 17 of the 24 dwellings, felt that their home was warmer since having the EWI installed. Occupants at 12% of the case study dwellings, which represents three of the 24 dwellings, felt that their home was not warmer since having the EWI installed. Finally, occupants at 17% of the case study dwellings, which represents four of the 24 dwellings, did not know whether their home was warmer or not since having the EWI installed.

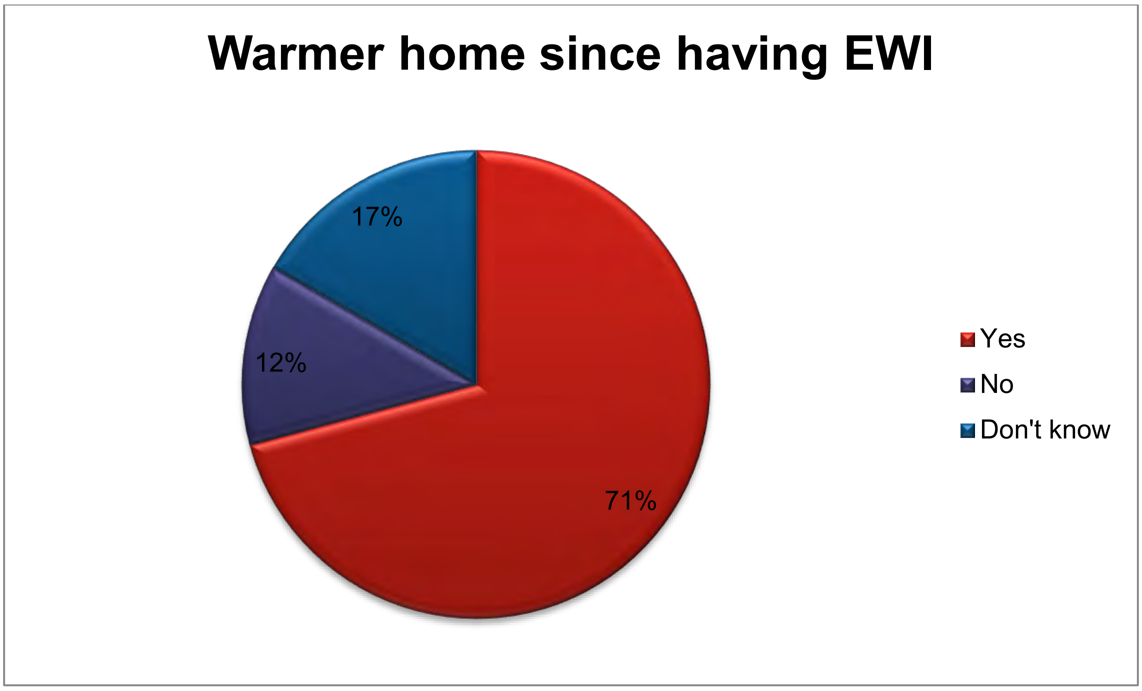


Figure 100: Pie chart illustrating answers to question one

For question two, the distribution of the answers are set out in the pie charts in Figures 101 to 103 below. As illustrated in the pie chart in Figure 101, occupants at 12% of the case study dwellings, which represent three of the 24 dwellings, stated they did not know whether they had increased the internal temperature inside their home. However, occupants at 21% of the case study dwellings, which represent five of the 24 dwellings, stated that they had increased the internal temperature inside their home during the heating season since having the EWI installed. In response to the corresponding sub-question, eight reasons were selected across the five dwellings, as illustrated in the pie chart in Figure 102. The explanation for there being eight reasons given is due to one occupant selecting the first four of the five options as their answer. Three of the occupants selected just the fourth option of liking it warmer but could not afford to keep their home warmer before the EWI was installed and one occupant selected 'other reason' as their answer. This other reason stated by the occupant was that they wanted increased "thermal comfort" in their home.

Occupants at the remaining 67% of the case study dwellings, which represents 16 of the 24 dwellings, stated that they had not increased the internal temperature in their home since having the EWI installed. In response to the corresponding sub-question, 18 reasons were selected across the 16 dwellings, as illustrated in the pie chart in Figure 103. Occupants at two of the dwellings selected the first option, which stated that they were trying to save money on their heating bill. Occupants at three of the dwellings selected option one and two, which stated that they were trying to save money on their heating bill and that their home does not feel as cold inside. Occupants at eight of the dwellings selected the second option, which stated that their home does not feel as cold inside. Finally, an occupant at one dwelling selected the third option of 'other reason' and specified that they had not increased the internal temperature of their home because they "cannot control the temperature [...] they can only turn their heating on or off".

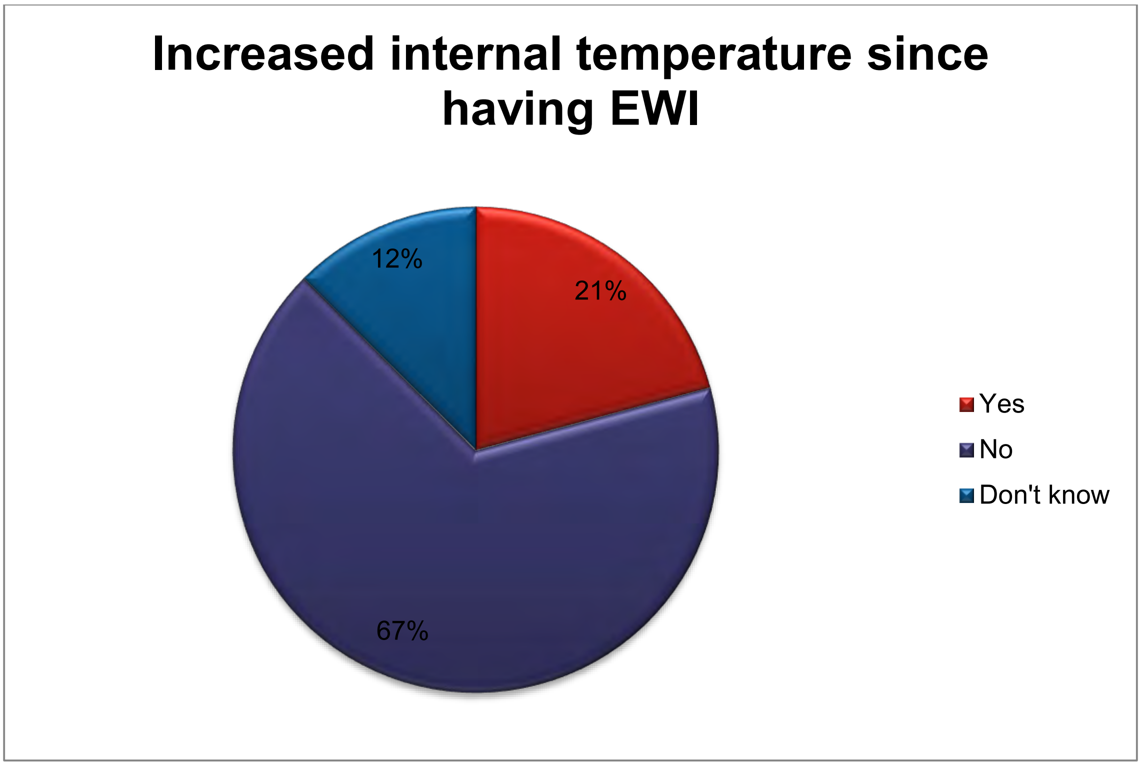


Figure 101: Pie chart illustrating answers to question two

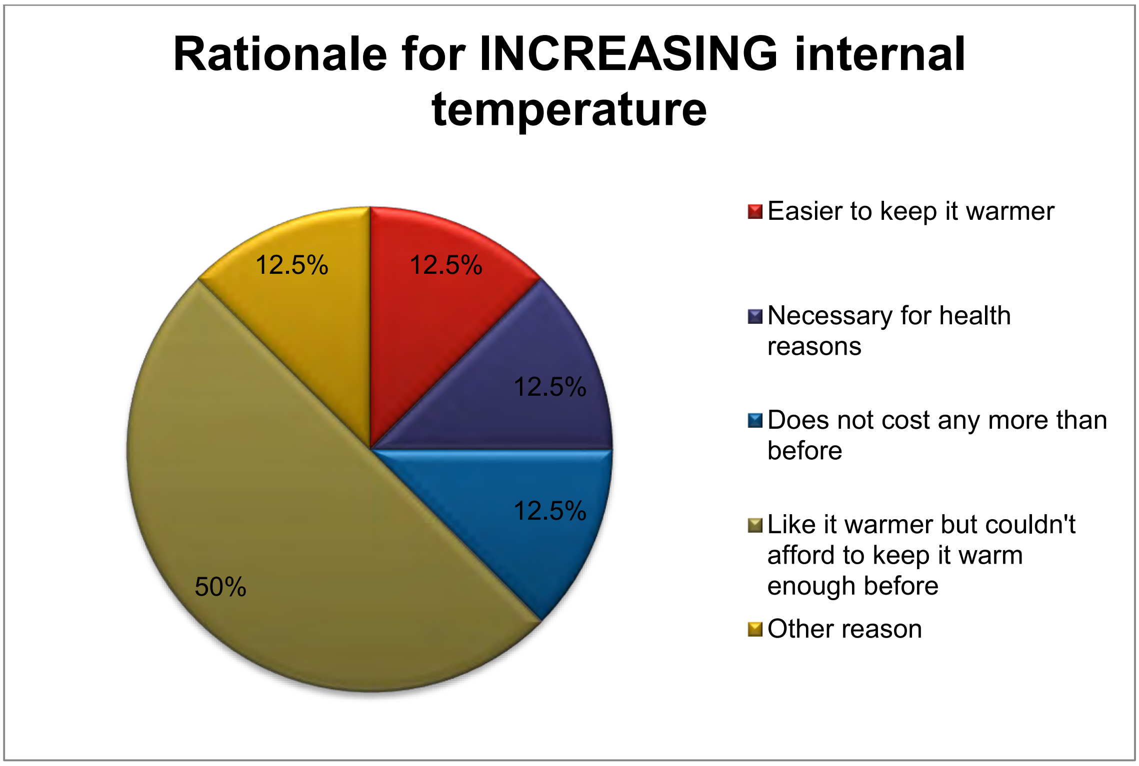


Figure 102: Pie chart illustrating rationale for occupants increasing the internal temperature since having the EWI installed

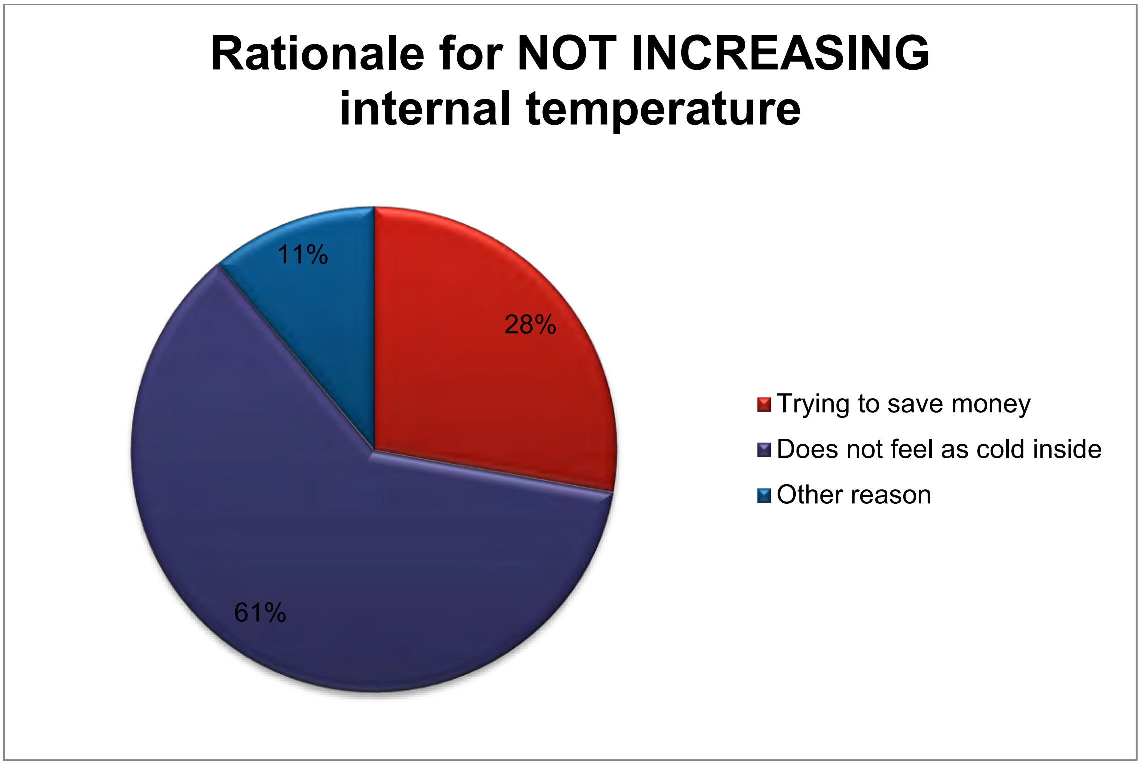


Figure 103: Pie chart illustrating rationale for occupants not increasing the internal temperature since having the EWI installed

### 5.3.2 Energy consumption and carbon emissions

A further aspect of the post-retrofit occupant surveys focused upon collecting energy company details, which supplied the Arbed I case study dwellings, along with consent to contact the companies directly for the energy consumption data. In addition, floor area measurements were taken, where these were not already provided by the housing associations, to enable the energy consumption and carbon emissions per square metre to be determined. These data were normalised using heating degree days to allow a comparison between pre-retrofit and post-retrofit energy consumption and carbon emissions to be made across two different heating seasons.

Whilst consent was provided from all 24 dwellings, which took part in the post-retrofit occupant surveys, complete pre-retrofit and post-retrofit energy consumption data was only collected for 12 Arbed I case study dwellings from the three energy companies which obliged to disclose the data. As discussed in sections 4.2.3 and 4.3.1, the reasons this data was not obtained from the other 12 dwellings was either due to incorrect information being provided by the occupants or the energy company not responding to requests for the data. Nevertheless, the data from the 12 Arbed I case studies represent all three dwelling types that received the retrofitted EWI: three dwellings are end-terrace; five are mid-terrace; and four are flats.

Tables 59 to 70 below set out the energy consumption and carbon emissions data for each of the 12 case study dwellings. Case studies I to III are the end-terrace dwellings, IV to VIII are the mid-terrace dwellings and IX to XII are the flats. Each table provides the pre-retrofit, post-retrofit and difference between the two for each of the: total energy consumption for the fuel used to heat the dwelling; total heating degree days for the 12 months either side of when the EWI was installed; energy consumption per heating degree day; normalised energy consumption; normalised energy consumption per square metre of floor area; quantity of carbon emissions that are emitted as a result of the energy consumption; and the quantity of carbon emissions emitted per square metre of floor area.

Using the formula set out in section 4.3.1, the energy consumption and carbon emissions have been normalised using the 20 year average heating degree days figure of 2037, which was obtained from Vesma (2013). The carbon emissions have been calculated using the conversion factors of 0.18404/kWh for gas and 0.44548/kWh for electricity; these were obtained from the Carbon Trust (2013). With the exception of Case Study IV, the total energy consumption is for the gas consumed at the dwellings as this is the fuel used for heating purposes. For Case Study IV, the total energy consumption is for electricity consumed as this dwelling does not have gas central heating; the main source of heat is from freestanding electrical heaters. All figures stated in the tables in this section have been rounded to nearest whole number, with the exception of the kWh per heating degree days. The rationale for this decision is that rounding these figures to nearest whole number had a significant impact on the results; thus this could have lead to misleading data being presented.

Whist every effort has been made to ensure the accuracy of the data provided by the energy companies, it was not possible to verify the figures. For case studies I, IV, V and VI the occupants pay their energy bills by monthly or quarterly direct debit and therefore it is possible that the consumption figures provided were based on estimates. However, the data provided was at least 24 to 36 months old when it was disclosed and therefore it is anticipated that any inaccuracies would have been identified prior to this time (July 2013). With the exception of Case Study XI, the occupants at the other seven case studies pay for their energy using a pre-payment meter and therefore the data provided is anticipated to be accurate. For Case Study XI the energy company explained that there had been an issue with the meter during the first six months of the pre-retrofit stage discussed and therefore the analysis has taken this into account.

### *Case Study I*

Case study I is an end-terrace two storey house, which is owner-occupied and has an internal floor area of 129m$^2$. The EWI was retrofitted in April 2011. Both a pre-retrofit and post-retrofit occupant survey was undertaken at this dwelling using structured interviews. At the pre-retrofit stage there were two occupants over the age of 65 years and in a typical week the dwelling was continuously occupied. Between the pre-retrofit (February 2011) and post-retrofit (October 2012) stages, the number of occupants reduced to one and the occupancy pattern change as during a typical weekday afternoon there is no one at home.

As set out in Table 59 below, the resulting annual pre-retrofit and post-retrofit normalised energy consumption and carbon emissions indicate that there has been a 4.69% overall reduction, which equates to just over 1000 kWh and 185 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt their home was warmer since having the EWI installed. However, they did not know whether they had increased the internal temperature inside their home. From the results set out Table 59 below, it would appear that the occupant has not increased the internal temperature in their home since having the EWI installed. Nevertheless, the reduction in energy consumption could be attributed to the change in occupancy pattern.

**Table 58: Energy consumption and carbon emissions data for Case Study I**

| Case Study I | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total gas consumption (kWh)** | 20605 | 14896 | -28% |
| **Total heating degree days (HDD)** | 1967 | 1492 | -475 |
| **kWh/HDD** | 10.475 | 9.984 | -5% |
| **Normalised kWh** | 21338 | 20337 | -5% |
| **Normalised kWh/m$^2$** | 165 | 158 | -5% |
| **Normalised $Kg_eCO_2$** | 3927 | 3742 | -5% |
| **Normalised $Kg_eCO_2/m^2$** | 30.44 | 29.01 | -5% |

### *Case Study II*

Case study II is an end-terrace house, which is rented from a private landlord and has an internal floor area of 126 $m^2$. The EWI was retrofitted in June 2011. The occupant survey was undertaken as a short postal questionnaire. At the time of the post-retrofit occupant survey (August 2012), there were five occupants; three were between five and 17 years of age and two were between 18 and 65 years. In a typical week the dwelling was continuously occupied throughout weekdays and weekends.

As set out in Table 60 below, the resulting pre-retrofit and post-retrofit normalised energy consumption and carbon emissions indicate that there has been a 5.21% overall increase, which equates to 616 kWh and 113 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt their home was warmer since having the EWI installed and they had not increased the internal temperature inside their home. However, the results of the energy consumption monitoring set out Table 60 below do not correspond with the occupant's response in the questionnaire. As there were no changes to the number of occupants or time spent at home, it appears that there have been some changes to occupant behaviour that is related to their gas use at home.

**Table 59: Energy consumption and carbon emissions data for Case Study II**

| Case Study II | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total gas consumption (kWh)** | 10739 | 9866 | -8% |
| **Total heating degree days (HDD)** | 1853 | 1618 | -235 |
| **kWh/HDD** | 5.795 | 6.097 | +5% |
| **Normalised kWh** | 11805 | 12421 | +5% |
| **Normalised kWh/m$^2$** | 94 | 99 | +5% |
| **Normalised $Kg_eCO_2$** | 2173 | 2286 | +5% |
| **Normalised $Kg_eCO_2/m^2$** | 17.24 | 18.14 | +5% |

### *Case Study III*

Case study III is an end-terrace house, which is rented from one of the housing associations and has an internal floor area of 110 m$^2$. The EWI was retrofitted in June 2011. The occupant survey was undertaken as a short postal questionnaire. At the time of the post-retrofit occupant survey (August 2012), there were three occupants; one between five and 17 years of age and two were between 18 and 65 years. In a typical week the dwelling was occupied in the mornings, evenings and at night throughout weekdays and continuously at weekends.

As set out in Table 61 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 5.99% overall increase, which equates to 925 kWh and 170 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt their home was warmer since having the EWI installed and they had not increased the internal temperature inside their home. However, the results of the energy consumption monitoring set out Table 61 below do not correspond with the occupant's response in the questionnaire as the increase indicates that some relative changes to occupant behaviour has been undertaken. Nevertheless, it is recognised that there could be other explanations for the additional consumption.

**Table 60: Energy consumption and carbon emissions data for Case Study III**

| Case Study III | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total gas consumption (kWh)** | 14041 | 12995 | -7% |
| **Total heating degree days (HDD)** | 1853 | 1618 | -235 |
| **kWh/HDD** | 7.577 | 8.013 | +5% |
| **Normalised kWh** | 15435 | 16360 | +6% |
| **Normalised kWh/m$^2$** | 140 | 149 | +6% |
| **Normalised Kg$_e$CO$_2$** | 2841 | 3011 | +6% |
| **Normalised Kg$_e$CO$_2$/m$^2$** | 25.82 | 27.37 | +6% |

### *Case Study IV*

Case study IV is a mid-terrace house, which is owner-occupied and has an internal floor area of 77 m$^2$. The EWI was retrofitted in June 2011. Both a pre-retrofit and post-retrofit occupant survey was undertaken at this dwelling using structured interviews. At the time of both the pre-retrofit and post-retrofit occupant surveys (February 2011 and September 2012, respectively), there were two occupants between 18 and 65 years. In a typical week at the pre-retrofit stage the dwelling was occupied in the afternoons, evenings and at night throughout weekdays and continuously at weekends. At the post-retrofit stage the dwelling was continuously occupied during weekdays and weekends in a typical week.

As set out in Table 62 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 13% overall increase, which equates to 983 kWh and 438 Kg$_e$CO$_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt their home was warmer since having the EWI installed and they did not know whether they had increased the internal temperature inside their home. The increase in energy consumption could be attributed to an increase of the internal temperature. However, the increase could also be attributed to the change in occupancy pattern, a combination of the two reasons or due to other reasons.

**Table 61: Energy consumption and carbon emissions data for Case Study IV**

| Case Study IV | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total electricity consumption (kWh)** | 5983 | 6005 | + <1% |
| **Total heating degree days (HDD)** | 1853 | 1618 | -235 |
| **kWh/HDD** | 3.228 | 3.711 | +13% |
| **Normalised kWh** | 6577 | 7560 | +13% |
| **Normalised kWh/m$^2$** | 85 | 98 | +13% |
| **Normalised $Kg_eCO_2$** | 2930 | 3368 | +13% |
| **Normalised $Kg_eCO_2/m^2$** | 38.04 | 43.73 | +13% |

### *Case Study V*

Case study V is a mid-terrace house, which is owner-occupied and has an internal floor area of 104m$^2$. The EWI was retrofitted in April 2011. Both a pre-retrofit and post-retrofit occupant survey was undertaken at this dwelling using structured interviews. At the time of both the pre-retrofit and post-retrofit occupant surveys (February 2011 and September 2012, respectively), there were one occupant over the age of 65 years. In a typical week at both the pre-retrofit and post-retrofit stage the dwelling was continuously occupied during weekdays and weekends.

As set out in Table 63 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 23.27% overall reduction, which equates to 2754 kWh and 507 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they did not know whether their home was warmer since having the EWI installed and they had not increased the internal temperature inside their home. The results set out in Table 63 below, appear to support the occupant's statement that they had not increased the internal temperature in their home since having the EWI installed. Nevertheless, it is recognised that in addition to the retrofitted EWI, there could be other explanations for the reductions in energy consumption.

**Table 62: Energy consumption and carbon emissions data for Case Study V**

| Case Study V | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total gas consumption (kWh)** | 11429 | 6652 | -42% |
| **Total heating degree days (HDD)** | 1967 | 1492 | -475 |
| **kWh/HDD** | 5.81 | 4.458 | -23% |
| **Normalised kWh** | 11836 | 9082 | -23% |
| **Normalised kWh/m$^2$** | 113 | 87 | -23% |
| **Normalised $Kg_eCO_2$** | 2178 | 1671 | -23% |
| **Normalised $Kg_eCO_2/m^2$** | 20.86 | 16.01 | -23% |

### *Case Study VI*

Case study VI is a mid-terrace house, which is owner-occupied and has an internal floor area of 75m$^2$. The EWI was retrofitted in June 2011. Both a pre-retrofit and post-retrofit occupant survey was undertaken at this dwelling using structured interviews. At the time of both the pre-retrofit and post-retrofit occupant surveys (February 2011 and September 2012, respectively), there was one occupant aged between 18 and 65 years. At the pre-retrofit stage the dwelling was continuously occupied during a typical week. At the post-retrofit stage the dwelling was typically occupied during weekday mornings, evenings and at night and during afternoons, evenings and at night at weekends.

As set out in Table 64 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 5.45% overall reduction, which equates to 698 kWh and 128 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt that their home was warmer since having the EWI installed and they had not increased the internal temperature inside their home. The results set out Table 64 below, appear to support the occupant's statement that they had not increased the internal temperature in their home since having the EWI installed. However, it is recognised that the reductions in energy consumption could also be attributed to the change in occupancy pattern.

**Table 63: Energy consumption and carbon emissions data for Case Study VI**

| **Case Study VI** | **Pre-retrofit** | **Post-retrofit** | **Difference** |
|---|---|---|---|
| **Total gas consumption (kWh)** | 11650 | 9618 | -17% |
| **Total heating degree days (HDD)** | 1853 | 1618 | -235 |
| **kWh/HDD** | 6.287 | 5.944 | -5% |
| **Normalised kWh** | 12806 | 12108 | -5% |
| **Normalised kWh/m$^2$** | 171 | 162 | -5% |
| **Normalised $Kg_eCO_2$** | 2357 | 2229 | -5% |
| **Normalised $Kg_eCO_2/m^2$** | 31.45 | 29.73 | -5% |

### *Case Study VII*

Case study VII is a mid-terrace house, which is rented from one of the housing associations and has an internal floor area of 110m$^2$. The EWI was retrofitted in June 2011. Both a pre-retrofit and post-retrofit occupant survey was undertaken at this dwelling using structured interviews. At the time of both the pre-retrofit and post-retrofit occupant surveys (March 2011 and October 2012, respectively), there were four occupants; two aged between five and 17 years and two aged between 18 and 65 years. At the pre-retrofit stage the dwelling was continuously occupied during a typical week. At the post-retrofit stage the dwelling was typically occupied during weekday mornings, evenings and at night and continuously at weekends.

As set out in Table 65 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 5.27% overall increase, which equates to 1312 kWh and 242 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt that their home was warmer since having the EWI installed and they had not increased the internal temperature inside their home. However, the results of the energy consumption monitoring set out Table 65 below do not correspond with the occupant's responses in the questionnaire, for both their behaviour and reduced occupancy pattern.

Table 64: Energy consumption and carbon emissions data for Case Study VII

| Case Study VII | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total gas consumption (kWh)** | 22649 | 20819 | -8% |
| **Total heating degree days (HDD)** | 1853 | 1618 | -235 |
| **kWh/HDD** | 12.222 | 12.867 | +5% |
| **Normalised kWh** | 24898 | 26210 | +5% |
| **Normalised kWh/m$^2$** | 226 | 238 | +5% |
| **Normalised $Kg_eCO_2$** | 4582 | 4824 | +5% |
| **Normalised $Kg_eCO_2/m^2$** | 41.66 | 43.85 | +5% |

## *Case Study VIII*

Case study VIII is a mid-terrace house, which is rented from one of the housing associations and has an internal floor area of 100 m$^2$. The EWI was retrofitted in June 2011. Both a pre-retrofit and post-retrofit occupant survey was undertaken at this dwelling using structured interviews. At the time of both the pre-retrofit and post-retrofit occupant surveys (May 2011 and October 2012, respectively), there were four occupants; two aged between five and 17 years and two aged between 18 and 65 years. At both the pre-retrofit and post-retrofit stage the dwelling was continuously occupied during a typical week.

As set out in Table 66 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 21.04% overall reduction, which equates to 6875 kWh and 1331 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt that their home was not warmer since having the EWI installed and they had not increased the internal temperature inside their home. The results set out in

Table 66 below, appear to support the occupant's statement that they had not increased the internal temperature in their home since having the EWI installed. Nevertheless, it is recognised that in addition to the retrofitted EWI, there could be other explanations for the reductions in energy consumption.

**Table 65: Energy consumption and carbon emissions data for Case Study VIII**

| **Case Study VIII** | **Pre-retrofit** | **Post-retrofit** | **Difference** |
|---|---|---|---|
| **Total gas consumption (kWh)** | 29865 | 20331 | -32% |
| **Total heating degree days (HDD)** | 1853 | 1618 | -235 |
| **kWh/HDD** | 16.117 | 12.565 | -22% |
| **Normalised kWh** | 32831 | 25956 | -21% |
| **Normalised kWh/m$^2$** | 327 | 256 | -22% |
| **Normalised Kg$_e$CO$_2$** | 6042 | 4711 | -22% |
| **Normalised Kg$_e$CO$_2$/m$^2$** | 60.16 | 46.90 | -22% |

## *Case Study IX*

Case study IX is a flat, which is rented from one of the housing associations and has an internal floor area of 73m$^2$. The EWI was retrofitted in September 2011. Both a pre-retrofit and post-retrofit occupant survey was undertaken at this dwelling using structured interviews. At the time of both the pre-retrofit and post-retrofit occupant surveys (May 2011 and October 2012, respectively), there two occupants aged between 18 and 65 years. In a typical week at both the pre-retrofit and post-retrofit stage the dwelling was occupied during evenings and at night during weekdays and during the afternoon, evening and at night during weekends.

As set out in Table 69 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 4.13% overall reduction, which equates to 494 kWh and 90 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt that their home was warmer since having the EWI installed and they had not increased the internal temperature inside their home The results set out Table 69 below, appear to support the occupant's statement that they had not increased the internal temperature in their home since having the EWI installed. Nevertheless, it is recognised that in addition to the retrofitted EWI, there could be other explanations for the reductions in energy consumption.

**Table 66: Energy consumption and carbon emissions data for Case Study IX**

| Case Study IX | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total gas consumption (kWh)** | 11169 | 9064 | -19% |
| **Total heating degree days (HDD)** | 1902 | 1610 | -292 |
| **kWh/HDD** | 5.872 | 5.629 | -4% |
| **Normalised kWh** | 11962 | 11468 | -4% |
| **Normalised kWh/m$^2$** | 164 | 157 | -4% |
| **Normalised $Kg_eCO_2$** | 2201 | 2111 | -4% |
| **Normalised $Kg_eCO_2/m^2$** | 30.16 | 28.91 | -4% |

## *Case Study X*

Case study X is a flat, which is rented from one of the housing associations and has an internal floor area of 44m$^2$. The EWI was retrofitted in June 2011. The occupant survey was undertaken as a short postal questionnaire in August 2012. The occupant, who completed and returned the questionnaire, did not specify the number and age of the occupants. In a typical week the dwelling was occupied continuously during weekdays and during mornings, evenings and at night during weekends.

As set out in Table 68 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 44.42% overall reduction, which equates to 1048 kWh and 193 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they did not know whether their home was warmer since having the EWI installed. They also stated that they did not know whether they had increased the internal temperature inside their home. The results set out Table 68 below, appear to indicate that the occupant had not increased the internal temperature in their home since having the EWI installed. Nevertheless, it is recognised that in addition to the retrofitted EWI, there could be other explanations for the reductions in energy consumption.

**Table 67: Energy consumption and carbon emissions data for Case Study X**

| Case Study X | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total gas consumption (kWh)** | 2147 | 1042 | -51% |
| **Total heating degree days (HDD)** | 1853 | 1618 | -235 |
| **kWh/HDD** | 1.158 | 0.644 | -44% |
| **Normalised kWh** | 2360 | 1312 | -44% |
| **Normalised kWh/m$^2$** | 54 | 30 | -44% |
| **Normalised $Kg_eCO_2$** | 434 | 241 | -44% |
| **Normalised $Kg_eCO_2/m^2$** | 9.87 | 5.49 | -44% |

### *Case Study XI*

Case study XI is a flat, which is rented from one of the housing associations and has an internal floor area of $63m^2$. The EWI was retrofitted in June 2011. Both a pre-retrofit and post-retrofit occupant survey was undertaken at this dwelling using structured interviews. At the time of both the pre-retrofit and post-retrofit occupant surveys (February 2011 and September 2012, respectively), there was one occupant aged between 18 and 65 years. At both the pre-retrofit and post-retrofit stage the dwelling was continuously occupied during a typical week. For this dwelling, the energy company only had data for the six months prior to the EWI being installed and not the full 12 months. However, upon analysing the data it was demonstrated that the occupant had consumed less gas in the 12 months after the EWI was installed compared to the six months prior. Therefore, it was decided to include this data as it provided significant evidence.

As set out in Table 69 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 12.58% overall reduction, which equates to 956 kWh and 175 $Kg_eCO_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt that their home was warmer since having the EWI installed and they had increased the internal temperature inside their home. In light of this information, this supports the argument above that the overall reduction in energy consumption and carbon emissions is greater than illustrated in Table 69 below.

**Table 68: Energy consumption and carbon emissions data for Case Study XI**

| Case Study XI | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total gas consumption (kWh)** | 6912 | 5276 | -24% |
| **Total heating degree days (HDD)** | 1853 | 1618 | -235 |
| **kWh/HDD** | 3.73 | 3.26 | -13% |
| **Normalised kWh** | 7598 | 6642 | -13% |
| **Normalised kWh/m$^2$** | 121 | 105 | -13% |
| **Normalised Kg$_e$CO$_2$** | 1398 | 1223 | -13% |
| **Normalised Kg$_e$CO$_2$/m$^2$** | 22.20 | 19.40 | -13% |

## *Case Study XII*

Case study XII is a flat, which is rented from one of the housing associations with an internal floor area of 35m$^2$. The EWI was retrofitted in June 2011. Both a pre-retrofit and post-retrofit occupant survey was undertaken at this dwelling using structured interviews. At the time of both the pre-retrofit and post-retrofit occupant surveys (March 2011 and September 2012, respectively), there was one occupant aged between 18 and 65 years. At both the pre-retrofit and post-retrofit stage the dwelling was continuously occupied during a typical week, with the exception of weekday mornings.

As set out in Table 70 below, the resulting pre-retrofit and post-retrofit energy consumption and carbon emissions indicate that there has been a 17.32% overall reduction, which equates to 153 kWh and 28 Kg$_e$CO$_2$ per year. With reference to thermal comfort perceptions and behaviour responses in the post-retrofit occupant survey for this particular dwelling, the occupant stated that they felt that their home was warmer since having the EWI installed and they had not increased the internal temperature inside their home. The results set out Table 70 below, appear to support the occupant's statement that they had not increased the internal temperature in their home. Nevertheless, it is recognised that in addition to the retrofitted EWI, there could be other explanations for the reductions in energy consumption.

**Table 69: Energy consumption and carbon emissions data for Case Study XII**

| Case Study XII | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Total gas consumption (kWh)** | 802 | 579 | -28% |
| **Total heating degree days (HDD)** | 1853 | 1618 | -235 |
| **kWh/HDD** | 0.432 | 0.357 | -17% |
| **Normalised kWh** | 882 | 729 | -17% |
| **Normalised kWh/m$^2$** | 25 | 21 | -17% |
| **Normalised $Kg_eCO_2$** | 162 | 134 | -17% |
| **Normalised $Kg_eCO_2/m^2$** | 4.64 | 3.83 | -17% |

### *Summary of energy monitoring results*

Overall 67% of the occupants at the 12 case study dwellings realised a reduction in their energy consumption and subsequent carbon emissions as a result of the retrofitted EWI and 33% increased their usage. The greatest reduction was 44% compared to the smallest reduction of 4%, which represents a 40% difference between the two reductions. Interestingly both of these dwellings are flats. The smallest increase was 5% and the largest increase was 13%, which represents an 8% difference. The former was an end-terrace dwelling and the latter was a mid-terrace. None of the flats saw an increase in energy consumption and carbon emissions. However, the average reduction across the eight dwellings was 15.125%, whereas the average increase was 7.25% across the other four dwellings. The graph in Figure 104 summarises the overall percentage of energy consumption change resulting from the retrofitted EWI.

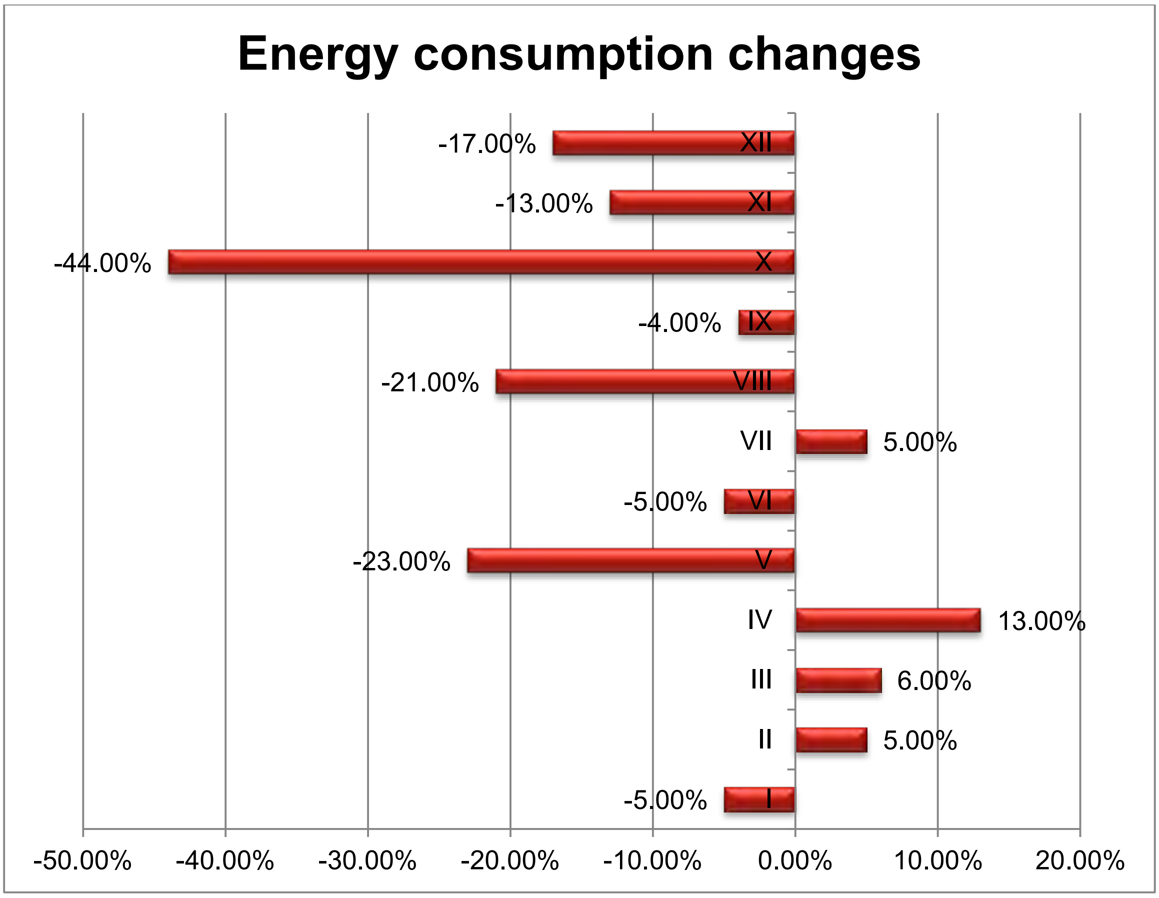


**Figure 104: Graph illustrating overall energy consumption changes resulting from the retrofitted EWI**

To summarise all the data presented in this chapter thus far, Table 71 below presents an overview to allow a comparison to be made. From the 12 case study dwellings, three are end-terrace houses, five are mid-terrace houses and four are flats. Four of the case studies are owner occupied (OO), one is rented privately (P) and the remaining seven are rented from one of the housing associations and therefore are social tenants (S). Four of the dwellings have single occupants. Two of the dwellings have two occupants. One of the dwellings has three occupants. Two of the dwellings have four occupants. One of the dwellings has five occupants. One of the dwellings had two occupants at the pre-retrofit stage and this reduced to one occupant at the post-retrofit stage. At one of the dwellings it was not declared how many occupants live there.

**Table 70: Summary of occupant survey results relative to energy consumption changes**

| **Case Study** | **I** | **II** | **III** | **IV** | **V** | **VI** | **VII** | **VIII** | **IX** | **X** | **XI** | **XII** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dwelling type | End-terrace | | | Mid-terrace | | | | | Flat | | | |
| Tenure | OO | P | S | OO | OO | OO | S | S | S | S | S | S |
| Number of occupants | 2<br>1 | 5 | 3 | 2 | 1 | 1 | 4 | 4 | 2 | ? | 1 | 1 |
| Continuous occupancy (Y/N) Pre-retrofit | Y | Y | N | N | Y | Y | Y | Y | N | Y | Y | N |
| Continuous occupancy (Y/N) Post-retrofit | N | Y | N | Y | Y | N | N | Y | N | Y | Y | N |
| Warmer since EWI (Y/N/DN) | Y | Y | Y | Y | DN | Y | Y | N | Y | DN | Y | Y |
| Increased temperature (Y/N/DN) | DN | N | N | DN | N | N | N | N | N | DN | Y | N |
| Percentage change (Energy use) | -5% | +5% | +6% | +13% | -23% | -5% | +5% | -21% | -4% | -44% | -13% | -17% |

Eight of the dwellings were continuously occupied throughout the day and night during a typical week and weekend at the pre-retrofit stage. This reduced at the post-retrofit stage to six dwellings which were continuously occupied during a typical week and weekend. Occupants at nine of the 12 dwellings felt their home was warmer since the EWI was installed. Occupants at two of the dwellings did not know of their home was warmer and one occupant said their home was not warmer since having the EWI installed. Occupants at eight of the 12 dwellings said they had not increased the internal temperature since having the EWI installed. Occupants at three of the dwellings said they did not know if they had increased the internal temperature and one said they had increased the internal temperature since having the EWI installed. Finally, energy consumption at eight of the dwellings reduced since having the EWI installed and increased at the other four dwellings.

### 5.3.3 Cost-effectiveness of the retrofitted EWI

From the 12 case studies to which energy consumption data was set out in section 5.3.2 above, energy cost data was also collected from the energy companies for ten of these dwellings (Case studies I to X). Based on the normalised energy consumption, pre-retrofit and post-retrofit energy costs are compared for each of the ten case study dwellings, which are set out in Tables 71 to 80 below.

#### *Case Study I*

To recap, Case Study I is an end-terrace dwelling, which had two occupants over the age of 65 years and was continuously occupied prior to the retrofitted EWI being installed. After the EWI was installed the number of occupants reduced to one and the dwelling was not occupied during weekday afternoons. The occupant stated that they felt their home was warmer and they did not know whether they had increased the internal temperature since having the EWI installed. Finally, energy consumption appeared to have reduced by approximately 5% per annum after the EWI was installed, based on normalised figures, thus indicating that the occupant had not increased the internal temperature.

Due to an 18% increase in energy costs between the pre-retrofit and post-retrofit stages for this dwelling, the figures in Table 72 indicate that the occupant is likely to realise an approximate overall 13% to 14% increase on their gas bill; this is based on the normalised energy costs. Nevertheless, this is 4% to 5% less than it would otherwise had been if the EWI had not been retrofitted. Furthermore, the following year (2012), this occupant's gas costs went up by a further 8%. As a result, it would appear that no energy cost savings will be realised at this dwelling; this is despite the indication that the occupant has not increased the internal temperature in their home, as well as the number of occupants and time spent at home reducing. In addition, the retrofitted EWI is very unlikely to assist with alleviating the occupants out of fuel poverty. The results indicate that the occupants are more likely to be in deeper fuel poverty.

**Table 71: Energy cost data for Case Study I**

| **Case Study I** | **Pre-retrofit** | **Post-retrofit** | **Difference** |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.03524 | 0.04308 | +18% |
| **Normalised kWh** | 21338 | 20337 | -5% |
| **Normalised costs (£)** | 751.95 | 876.12 | +14% |

### *Case Study II*

To recap, Case study II is an end-terrace house with five occupants (three between five and 17 years of age and two between 18 and 65 years), which was continuously occupied throughout weekdays and weekends. The occupants stated that they felt their home was warmer and had not increased the internal temperature since having the EWI installed. Finally, energy consumption appeared to have increased by approximately 5% per annum after the EWI was installed, thus indicating that some changes to occupant behaviour towards energy use have occurred.

Due to an 18% increase in energy costs between the pre-retrofit and post-retrofit stages, the figures in Table 73 indicate that the occupants are even more unlikely to realise any savings on their gas bill; this is based on the normalised energy costs, which indicate an overall approximate 22% to 23% increase. Furthermore, the following year (2012), this occupant's gas costs went up by a further 3%. As a result, the retrofitted EWI is very unlikely to assist with alleviating the occupants out of fuel poverty. The results indicate that the occupants are more likely to be in deeper fuel poverty.

**Table 72: Energy cost data for Case Study II**

| Case Study II | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.03935 | 0.04825 | +18% |
| **Normalised kWh** | 5.795 | 6.097 | +5% |
| **Normalised costs (£)** | 11805 | 12421 | +5% |

### *Case Study III*

To recap, Case Study III is an end-terrace house with three occupants (one between five and 17 years of age and two were between 18 and 65 years), which was occupied in the mornings, evenings and at night throughout weekdays and continuously at weekends. The occupants stated that they felt their home was warmer and they had not increased the internal temperature since having the EWI installed. Finally, energy consumption appears to have increased by approximately 6%, which indicates that some changes in occupant behaviour towards energy use have occurred since the EWI was installed.

Due to a 15% increase in energy costs between the pre-retrofit and post-retrofit stages, the figures in Table 74 indicate that occupants are even more unlikely to realise any savings on their gas bill; this is based on the normalised energy costs, which indicate an overall approximate 20% to 21% increase. As a result, the retrofitted EWI is very unlikely to assist with alleviating the occupants out of fuel poverty. The results indicate that the occupants are more likely to be in deeper fuel poverty.

**Table 73: Energy cost data for Case Study III**

| Case Study III | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.03464 | 0.04086 | +15% |
| **Normalised kWh** | 15435 | 16360 | +6% |
| **Normalised costs (£)** | 534.67 | 668.47 | +20% |

### *Case Study IV*

To recap, Case study IV is a mid-terrace house with two occupants between 18 and 65 years, which was occupied in the afternoons, evenings and at night throughout weekdays and continuously at weekends at the pre-retrofit stage. At the post-retrofit stage the dwelling was continuously occupied during weekdays and weekends in a typical week. The occupants stated that they felt their home was warmer and they did not know whether they had increased the internal temperature since having the EWI installed. Finally, energy consumption appears to have increased by approximately 13%, which indicates that some changes in occupant behaviour towards energy use have occurred since the EWI was installed.

Due to a 4% increase in energy costs between the pre-retrofit and post-retrofit stages, the figures in Table 75 indicate that occupants are even more unlikely to realise any savings on their electricity bill; this is based on the normalised energy costs, which indicates an overall approximate 17% increase. Furthermore, the following year (2012), this occupant's electricity costs went up by a further 7%. As a result, the retrofitted EWI is unlikely to assist with alleviating the occupants out of fuel poverty. The results indicate that the occupants are more likely to be in deeper fuel poverty.

**Table 74: Energy cost data for Case Study IV**

| Case Study IV | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.13071 | 0.13650 | +4% |
| **Normalised kWh** | 6577 | 7560 | +13% |
| **Normalised costs (£)** | 859.68 | 1031.94 | +17% |

### *Case Study V*

To recap, Case study V is a mid-terrace house with one occupant over the age of 65 years, which was continuously occupied during weekdays and weekends. The occupant stated that they did not know whether their home was warmer or not and had not increased the internal temperature since having the EWI installed. Finally, energy consumption has been reduced by approximately 23%, which appears to confirm that the occupant has not increased the internal temperature since the EWI was installed.

Due to a 28% increase in energy costs between the pre-retrofit and post-retrofit stages, the figures in Table 76 indicate that the occupant is likely to realise an approximate overall 5% to 7% increase on their gas bill; this is based on the normalised energy costs. Nevertheless, this is 23% less than it would otherwise had been if the EWI had not been retrofitted. The following year (2012), this occupant's gas costs went down by 7%. Therefore, it is likely that the occupant would have returned to the same level of energy costs as before the EWI was installed or potentially realised an approximate saving of 2%. As a result, the retrofitted EWI is unlikely to have assisted with alleviating this occupant out of fuel poverty.

**Table 75: Energy cost data for Case Study V**

| Case Study V | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.03857 | 0.05386 | +28% |
| **Normalised kWh** | 11836 | 9082 | -23% |
| **Normalised costs (£)** | 456.51 | 489.16 | +7% |

### *Case Study VI*

To recap, Case study VI is a mid-terrace house with one occupant aged between 18 and 65 years, which was continuously occupied during a typical week at the pre-retrofit stage. At the post-retrofit stage the dwelling was typically occupied during weekday mornings, evenings and at night and during afternoons, evenings and at night at weekends. The occupant stated that they felt that their home was warmer and they had not increased the internal temperature since having the EWI installed. Finally, the energy consumption had reduced by approximately 5%, which appears to confirm that the occupant has not increased the internal temperature since the EWI was installed.

Due to an 18% increase in energy costs between the pre-retrofit and post-retrofit stages, the figures in Table 77 indicate that the occupant is likely to realise an approximate overall 13% increase on their gas bill; this is based on the normalised energy costs. Nevertheless, this is 5% less than it would otherwise had been if the EWI had not been retrofitted. The following year (2012), this occupant's gas costs went up by a further 1%. As a result, it appears that the retrofitted EWI is unlikely to assist with alleviating this occupant out of fuel poverty. The results indicate that the occupants are more likely to be in deeper fuel poverty.

**Table 76: Energy cost data for Case Study VI**

| Case Study VI | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.03894 | 0.04736 | +18% |
| **Normalised kWh** | 12806 | 12108 | -5% |
| **Normalised costs (£)** | 498.67 | 573.44 | +13% |

### *Case Study VII*

To recap, Case study VII is a mid-terrace house with four occupants (two aged between five and 17 years and two aged between 18 and 65 years), which was continuously occupied during a typical week at the pre-retrofit stage. At the post-retrofit stage the dwelling was typically occupied during weekday mornings, evenings and at night and continuously at weekends. The occupants stated that their home was warmer and they had not increased the internal temperature since the EWI was installed. Finally, energy consumption was increased by approximately 5% per annum, which indicates that some changes in occupant behaviour towards energy use have occurred since the EWI was installed.

Due to a 16% increase in energy costs between the pre-retrofit and post-retrofit stages, the figures in Table 78 indicate that occupants are even more unlikely to realise any savings on their gas bill; this is based on the normalised energy costs, which indicate an overall approximate 20% to 21% increase. Furthermore, the following year (2012), this occupant's gas costs went up by a further 9%. Therefore, it is likely that the occupant would have realised a total increase of 29% to 30% on their energy costs after the latter energy cost change. As a result, the retrofitted EWI is very unlikely to assist with alleviating the occupants out of fuel poverty. The results indicate that the occupants are more likely to be in deeper fuel poverty.

**Table 77: Energy cost data for Case Study VII**

| Case Study VII | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.03599 | 0.04279 | +16% |
| **Normalised kWh** | 24898 | 26210 | +5% |
| **Normalised costs (£)** | 896.08 | 1121.53 | +20% |

### *Case Study VIII*

To recap, Case study VIII is a mid-terrace house with four occupants (two aged between five and 17 years and two aged between 18 and 65 years). At both the pre-retrofit and post-retrofit stage the dwelling was continuously occupied during a typical week. The occupants stated that they felt their home was not warmer and they had not increased the internal temperature since having the EWI installed. Finally, energy consumption was reduced by approximately 21% per annum, which appears to confirm that the occupants have not increased the internal temperature.

Due to a 25% increase in energy costs between the pre-retrofit and post-retrofit stages, the figures in Table 79 indicate that the occupant is likely to realise an approximate overall 4% to 5% increase on their gas bill; this is based on the normalised energy costs. Nevertheless, this is 20% to 21% less than it would otherwise had been if the EWI had not been retrofitted. The following year (2012), this occupant's gas costs went down by 2%. Therefore, it is likely that the occupant would have only realised a 2% to 3% overall increase on their gas bill. As a result, the retrofitted EWI is unlikely to have assisted with alleviating this occupant out of fuel poverty.

**Table 78: Energy cost data for Case Study VIII**

| Case Study VIII | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.03498 | 0.04657 | +25% |
| **Normalised kWh** | 32831 | 25956 | -21% |
| **Normalised costs (£)** | 1148.43 | 1208.77 | +5% |

### *Case Study IX*

To recap, Case study IX is a flat with two occupants aged between 18 and 65 years, which was occupied during evenings and at night during weekdays and during the afternoon, evening and at night during weekends. The occupants stated that they felt their home was warmer and they had not increased the internal temperature since having the EWI installed. Finally, energy consumption was reduced by approximately 4% per annum, which appears to confirm that the occupants had not increased the internal temperature in their home,

Due to a 13% increase in energy costs between the pre-retrofit and post-retrofit stages, together with a 9% reduction in normalised costs, the figures in Table 80 indicate that the occupant is unlikely to realise any savings on their gas bills. Equally, it appears that the occupant has not seen an increase in their gas bill either. Nevertheless, as a result, the retrofitted EWI is unlikely to have assisted with alleviating this occupant out of fuel poverty.

**Table 79: Energy cost data for Case Study IX**

| Case Study IX | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.04705 | 0.05397 | +13% |
| **Normalised kWh** | 11962 | 11468 | -4% |
| **Normalised costs (£)** | 562.81 | 618.93 | -9% |

### *Case Study X*

To recap, Case study X is a flat and the number and age of occupants are unknown. However, in a typical week the dwelling was occupied continuously during weekdays and during mornings, evenings and at night during weekends. The occupant sated that they did not know whether their home was warmer or if they had increased the internal temperature since having the EWI installed. Finally, energy consumption was reduced by approximately 44% per annum, which indicates that the occupant had not increased the internal temperature in their home.

Due to a 36% increase in energy costs between the pre-retrofit and post-retrofit stages, together with a 14% reduction in normalised costs, the figures in Table 81 indicate that the occupant is likely to realise a 22% saving on their gas bills. As a result, it appears that the retrofitted EWI is likely to have assisted with alleviating this occupant out of fuel poverty. However, it is recognised that there are other factors that affect whether or not an occupant is in fuel poverty. Therefore, it is possible that occupant remains in fuel poverty.

**Table 80: Energy cost data for Case Study X**

| Case Study X | Pre-retrofit | Post-retrofit | Difference |
|---|---|---|---|
| **Unit costs (£/kWh)** | 0.05314 | 0.08261 | +36% |
| **Normalised kWh** | 2360 | 1312 | -44% |
| **Normalised costs (£)** | 125.41 | 108.38 | -14% |

### *Summary of energy costs*

The increases in energy costs have resulted in 9 of the 10 dwellings not realising any financial savings as a result of the retrofitted EWI and thus no alleviation from fuel poverty. The graph in Figure 105 illustrates the overall energy cost percentage changes, relative to energy consumption changes resulting from the retrofitted EWI, which takes into account energy price changes that occurred for each dwelling between the pre-retrofit and post-retrofit stages. Whilst the retrofitted EWI has reduced the effect of the energy price increases at six of the ten case study dwellings, the overall energy cost results are likely to have a significant impact on the payback of the retrofitted EWI.

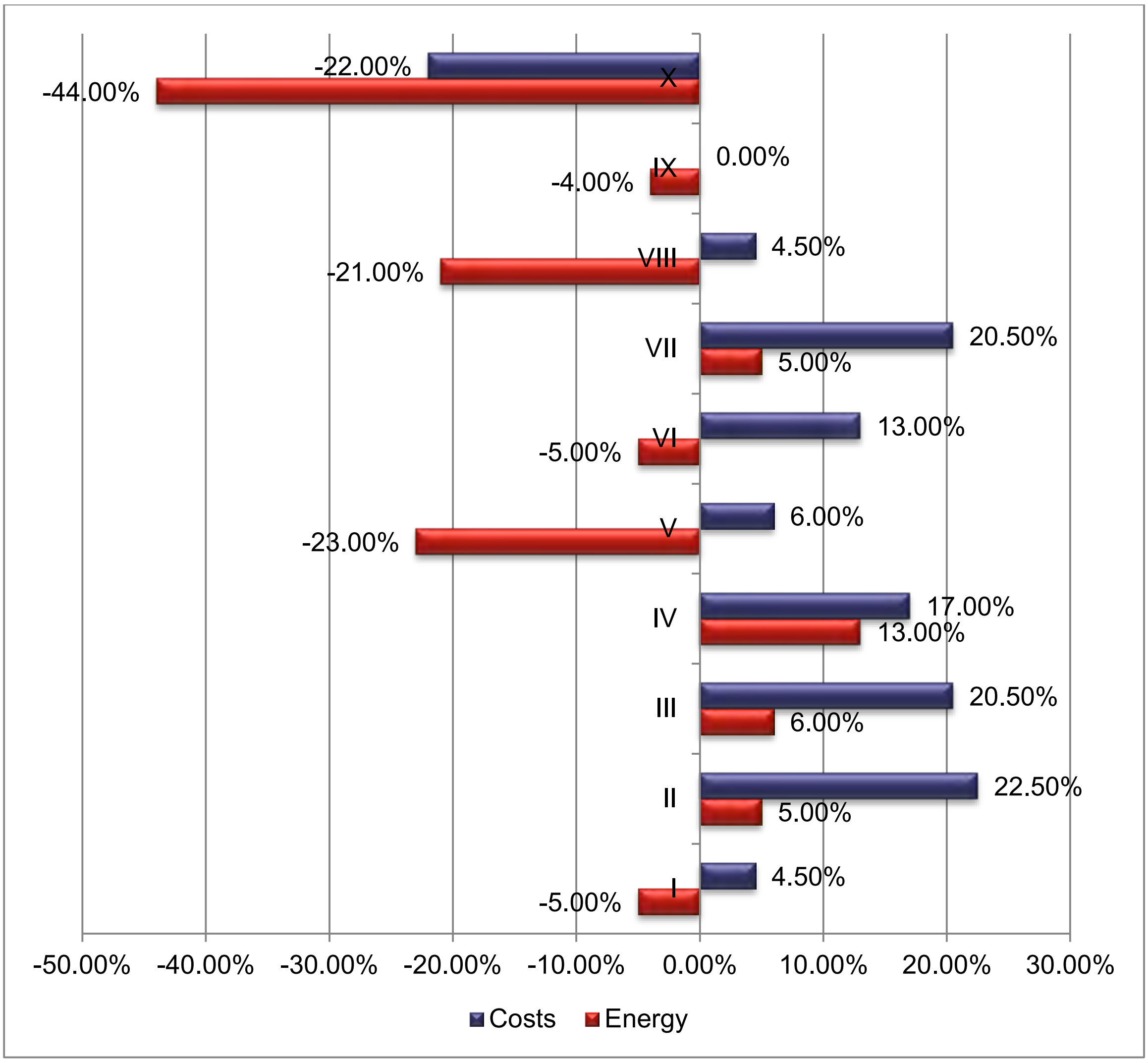


**Figure 105: Graph illustrating overall energy and cost differences resulting from the retrofitted EWI**

### *EWI payback*

Only limited capital cost data for retrofitting the EWI was available from one of the housing associations. The capital cost data that was provided was for two types of mid-terrace house (with and without a rear annexe), and included all additional works and preliminaries. The additional works included replacing fascias, gutters, downpipes and window sills, as well as temporarily removing and re-fixing fixtures, such as satellite dishes, aerials, washing lines and outside taps. The preliminaries included scaffolding, skips, personal protective equipment, sanitary facilities and labour. The breakdown for the two types of mid-terrace dwellings is set out in Table 81 below. However, it should be noted that these costs are based on 40 dwellings (20 of each type) being retrofitted as part of a whole street approach and therefore the costs for the preliminaries are not representative of a single dwelling installation. Nevertheless, this data is representative of three of the 10 Arbed I case study dwellings from section 5.3.2, as well as this section.

**Table 81: EWI cost breakdown for two types of mid-terrace dwellings**

| | Mid-terrace dwelling | |
|---|---|---|
| | With Rear Annexe | Without Rear Annexe |
| **Total external wall area** | 79m$^2$ | 48m$^2$ |
| **EWI costs** | £4859 | £2952 |
| **Additional works costs** | £4394 | £2496 |
| **Preliminaries costs** | £1995 | £1995 |
| **Total costs** | £11248 | £6443 |

Case Studies IV to VI are mid-terrace dwellings with annexes at the rear and were part of a whole-street approach. However, due to there being no energy cost savings at any of these case study dwellings, it can be determined without any further analysis that the retrofitted EWI will not pay for itself. Therefore, to establish if this lack of payback is due to the exceptionally high energy price increase during the 12 months after the EWI was installed, a basic cost analysis has been undertaken which is solely based on the occupant's pre-retrofit energy costs at the these three case study dwellings. This basic analysis is set out in Table 82 below. From the analysis, it can be determined that it will take Case Study V approximately 89 years for the EWI to pay for itself and 414 years for

Case Study VI. As Case Study IV increased their energy consumption, there is no payback for the EWI even where only pre-retrofit energy costs are used. It should be noted that this basic cost analysis does not take into account any other current or future energy price increases. Nevertheless, whilst it could be determined that Case Study's V and VI will maintain a 23% and 5% saving relative to current and future energy costs, as there was no immediate saving the payback will never be realised.

**Table 82: Basic payback cost analysis for retrofitted EWI at three mid-terrace dwellings**

| | Case studies | | |
|---|---|---|---|
| | **IV** | **V** | **VI** |
| **Pre-retrofit energy costs (£/kWh)** | 0.13071 | 0.03857 | 0.03894 |
| **Pre-retrofit annual normalised energy consumption (kWh)** | 6577 | 11836 | 12807 |
| **Post-retrofit annual normalised energy consumption (kWh)** | 7560 | 9082 | 12109 |
| **Difference in annual normalised energy consumption (kWh)** | + 983 (13%) | - 2754 (23%) | - 698 (5%) |
| **Difference in annual normalised energy costs (£)** | + £128.49 | - £126.22 | - £27.18 |
| **Payback (Years)** | Never | 89 | 414 |

## Chapter summary

The purpose of this chapter was to set out the results of the data collected using the methodology set out in Chapter Four. Commencing with the demographic data, this is followed by the construction quality data and then the energy performance data. The demographic data sets out the number of case study dwellings according to the: geographical location; dwelling types; number of occupants per dwelling; and the age of the occupants within the households. For the construction quality section, the data was presented in the following order: photographs; technical details; and thermographic surveys. The 25 photographs range from the very early stages to the completion, along with general overviews to very detailed images of specific details. The five technical details of the main junctions were produced using the photographs and on-site observations and provide a valuable link to the thermographic surveys. The thermographic surveys were set out for the seven case study dwellings, one at a time, illustrating the pre-retrofit images before the post-retrofit. Each case study included the environmental data collected at the time of the surveys.

The energy performance data commenced with the results of the occupants thermal comfort perceptions and behaviour data from the occupant surveys. This was followed by the energy consumption and carbon emissions data and concluded with the cost data. The thermal comfort perceptions and behaviour data was collected from 24 case study dwellings and focused upon the answers given to two specific questions:

1. Do you feel that your home is warmer since it has been insulated?
2. Have you increased the internal temperature that you keep your home at during the heating season (winter) since having the external wall insulation installed?

For the 24 case study dwellings, occupants at 71% felt their home was warmer, 12% felt their home was not warmer and 17% did not know if their home was warmer or not. In answer to the second question, occupants at 67% of the case study dwellings said they had not increased the internal air temperature since having the EWI installed, 21% said they had increased the internal air temperature and 12 % said they did not know if they had or not.

The energy consumption and carbon emissions data was supported by the floor area measurements and the heating degree days figures; these were collected for 12 dwellings. For each of the 12 case study dwellings, the following information was set out in a table for the 12 month pre-retrofit stage, 12 month post-retrofit stage and the percentage difference between the two: total consumption (gas or electricity); total heating degree days (HDD); kWh/HDD; Normalised kWh; Normalised kWh/m$^2$; Normalised $Kg_{eq}CO_2$; and Normalised $Kg_{eq}CO_2/m^2$. In addition, the answers given to the two thermal comfort and behaviour questions were discussed in relation to the energy consumption data. This section concluded with a graph illustrating the energy consumption changes as percentages for each of the 12 case study dwellings, as well as a table providing an overview of the demographic and thermal perception and behaviour data. Overall 33% of the case study dwellings saw an increase in their energy consumption and 77% saw a reduction. However, only 25% (three dwellings) saw a reduction greater than 20% and these were the only three dwellings where the occupants said they did not feel their home was warmer since having the EWI installed.

Finally, cost data was presented for the first ten of the 12 dwellings where energy consumption data was presented in the previous section. As with the energy consumption data, the following information was set out for the 12 month pre-retrofit stage; 12 month post-retrofit and the percentage difference for the two: unit costs (£/kWh); Normalised kWh; and Normalised costs (£). These results were also discussed in relation the energy consumption data and thermal comfort perceptions and behaviour data. This section concluded with the cost percentage changes added to the same graph illustrated at the end of the previous section; this demonstrates the differences between consumption and cost for each of the case study dwellings. However, in contrast to the energy consumption percentage changes, only one dwelling saw a reduction in energy costs and this was at the case study dwelling that saw a 44% reduction. The cost data was also used to calculate the EWI payback for three dwellings where there was sufficient data. Due to the energy cost increases after the EWI was installed, pre-retrofit cost data had to be used for the calculations, and otherwise no payback would have been demonstrated. Nevertheless, this was still the case for one of the three case study dwellings. Payback for the other two dwellings was 89 and 414 years, which are both beyond the life expectancy of the EWI system.

# Chapter 6: Discussion

# Chapter 6: Discussion

As set out in Chapter Two of this thesis, the UK and devolved governments have set targets to combat three significant issues: climate change, energy security and fuel poverty. Thus, the motivation for this doctoral research project was built upon the recognition of the relationship between these issues, together with the energy efficiency of existing dwellings in the UK. In Chapter Two it was set out that domestic buildings account for the second largest proportion of carbon emissions in the UK. Therefore, enhancing the energy efficiency of existing dwellings in the UK is central to making a contribution to the necessary improvements and thus reducing the impact of climate change, energy insecurity and fuel poverty.

This argument was further enhanced in Chapter Two of this thesis by the apparent correlation between the age and construction of existing dwellings, as well as their theoretical overall thermal performance in England and, in particular, Wales. Furthermore, Wales has significantly more pre-1919 dwellings than any other country in the UK. The significance of this is that the construction up to circa.1919 was predominantly traditional methods using solid walls, which have the poorer heat loss of the two main wall construction types: solid and cavity walls. In Chapter Two, section 2.4.2 it was demonstrated that improving the thermal performance of cavity walls is significantly easier and cheaper to implement.

In recognition that improving the energy efficiency of existing dwellings will make a significant contribution to meeting the targets and thus reduce carbon emissions, a number of policy drivers and strategies aimed specifically at these buildings were also discussed in Chapter Two of this thesis. These included: Part L of the Building Regulations; Energy Performance Certificates (EPCs); the Green Deal and Energy Company Obligation (ECO); and Arbed. One of the most significant drivers is argued by the author to be Part L of the Building Regulations as compliance with these is triggered by other works that are regularly undertaken in many domestic buildings. For example, re-plastering more than 25% of the internal surface of an external wall within any given room, as well as works involving energy consuming services, such as the central heating system.

The next significant driver is EPCs, which are required for every dwelling at the point of sale or lease. These provide an energy efficiency rating for the dwelling, as well as make recommendations on how this can be improved. As explained in Chapter Two, this driver will be further enhanced with the introduction of a minimum E rating on an EPC for rented dwellings from 2016. Further significant drivers for improving the energy efficiency of existing dwellings, which were also discussed in Chapter Two of this thesis, are the UK Government's Green Deal and ECO counterpart, as well as the Welsh Government's Arbed scheme and in addition to implementing measures for low income households, a significant proportion of the ECO is funding solid wall insulation. However, the anticipated repercussions were increased energy costs and a subsequent increase in levels of fuel poverty, rather than realising a reduction. As a method of addressing fuel poverty at both public and privately owned existing dwellings in Wales, as well as contribute to the 3% annual carbon emissions reduction target, the Welsh Government set up the Arbed scheme in 2009.

However, common issues were identified by the author of this thesis with all of these drivers, in particular for older traditionally built dwellings. As well as the use of a standard occupancy, which by definition will only reflect the actual household type, one of the main issues is the use of a standard u-value of 2.1 $W/m^2K$ for solid walls and the assumption that there will be continuity of retrofitted insulation. Furthermore, baselines, targets and assessments for improvements in energy performance are based on assumptions and models, rather than empirical data. Specifically, the primary adopted methodology for assessing the thermal performance of existing dwellings is rdSAP, which can lead to significant misleading results. These misleading results are thus likely to lead to claims of reductions in energy consumption, carbon emissions and fuel poverty being claimed, where in fact this has not been achieved.

Specifically for Arbed I, the lack of methodology for monitoring and evaluating the effectiveness of the interventions installed are likely to result in many of the lessons not being learnt prior to the instigation of Arbed II. Whilst some lessons were learnt prior to the commencement of Arbed II, this phase started before these were published. However, some results (Woosey, 2012; and Patterson, 2012), which were published in time for Arbed II, had data missing and relied upon theoretical and modelled data as this is all that was available in the timescales dictated. In addition, not all the information published appeared to be impartial and objective. For example, Patterson (2012) was not able to criticise the project manager and thus only attempted to focus upon the positive aspects of the findings.

To address some of the fundamental gaps in knowledge summarised in this chapter thus far, it is recognised that the interpretation of empirical data is central to maximising the accuracy of the lessons learnt, as well as informing other future EWI retrofit programmes. This doctoral research project has focused upon collecting and analysing empirical data to assess the effectiveness of the retrofitted EWI through Arbed I in Swansea. Based on established building performance evaluation techniques, as set out in Chapter Three above, three sets of data were collected and analysed to assess each of the construction quality of the EWI installations and the energy performance of the cases study dwellings. In addition, as discussed in Chapter Four above, a mixed-methods approach of collecting both qualitative and quantitative data was undertaken. Collectively, this approach has allowed for a comprehensive case study to be developed for retrofitted EWI at pre-1919 dwellings through phase one of the Arbed schemes.

The field observations undertaken to collect the qualitative data used to assess the construction quality consisted of: photographs taken before, during and after installations; production of technical details as they were installed on site at critical junctions; and pre-retrofit and post-retrofit thermographic surveys to compare whole-house heat loss, as well as to identify any thermal bridging. The methods undertaken to collect the primary quantitative data used to assess the energy performance of the existing dwellings consisted of occupant surveys and energy consumption monitoring. These were complemented by secondary data in the form of costing information and floor areas from the housing associations, along with heating degree days from the local weather station.

Using a combination of photographs, as-installed technical details and thermographic images, provided a robust method of assessing the occurrence of thermal bridging and thus the construction quality if the retrofitted EWI. The photographs provide an accurate record of the implementation and present valuable information for interpreting the other two data. The technical details allow for a direct comparison to design intentions and provide valuable information to support the interpretation of the photographs and thermal images. Finally, the thermal images provide an accurate method of ‘seeing heat’ and the methodology set out in this doctoral research provides consistency and thus robustness, as well as present valuable information to support the interpretation of the results.

In addition to the benefits of thermographic surveys, which were set out in Chapter Two, a further finding was confirmed during this study. To recap, at the pre-retrofit stage, thermographic surveys provide a good tool for assessing areas of the external fabric where there is significant heat loss and thus provide a graphical illustration of where to focus energy efficiency improvement measures. At the post-retrofit stage, external thermographic surveys appear to provide a good tool for assessing the continuity of retrofitted EWI and thus identification of thermal bridges, along with quality of workmanship to ensure design intentions are achieved for improving the energy efficiency of existing dwellings. However, whilst it was difficult to compare pre-retrofit and post-retrofit whole facade heat loss where thermographic surveys were undertaken at the wrong time of the year (summer), thermal bridging is still identifiable. In fact, it appears that the thermal bridging is clearer to see. Therefore, external qualitative thermography can potentially still be done outside the recommended times of the year. This is a sentiment of Ray Faulkner, who states that it is just necessary to understand the environmental conditions to maximise accuracy of interpretation. Otherwise thermography could never be done commercially.

For the energy performance data, the omission of the energy consumption data from the occupants could have prevented this aspect of this doctoral research project from being undertaken. However, due to the good rapport that the author of this thesis established with occupants during the pre-retrofit occupant surveys, it was possible to obtain consent to acquire this vital data directly from the energy suppliers. Despite additional barriers, such as being provided the wrong information by the occupants and some of the energy companies not being forthcoming with the data, complete energy consumption data was acquired for 12 case study dwellings. Having this empirical data has transformed this aspect of this doctoral research project from being average and thus the same as other studies to being original and significant. In addition, this was backed up with thermal comfort perceptions, which were integral to the energy performance analysis. Due to thermal comfort perceptions determining the use of heating and the acknowledgment that differences in behaviour can vary energy consumption by up to 300%, these data provided a third dimension to the results.

Collectively, the findings from analysing the data using these robust methods meet the aim: *to investigate the construction quality of retrofitted external wall insulation and resulting impact on energy efficiency at existing dwellings in Swansea.* In meeting this aim the overarching research question is also subsequently answered, which is: *How effective was the retrofitted external wall insulation, in terms of quality and impact on energy efficiency and thermal comfort levels, at the Arbed I case study dwellings in Swansea?*

The key findings from each of the construction quality and energy performance results are discussed in sections 6.1 and 6.2, respectively. This is followed by a summary of the contribution these findings have made to knowledge in section 6.3. Section 6.4 then sets out the limitations of this doctoral research project.

Finally, sections 6.5 and 6.6 conclude this chapter with a summary of further work that could be undertaken and recommendations, respectively.

## 6.1 Key findings from the construction quality data

This section discusses the key findings from the construction quality data (photographs, technical details and thermal images), which seeks to meet objective one and two of this doctoral research project. Objective one: *to appraise the implementation and execution of retrofitted external wall insulation at the Arbed I case study dwellings, to determine the effects on the quality of the installations.* Objective two: *To determine the value of and the need for non-invasive investigation techniques to confirm the construction quality and thermal integrity of retrofitted external wall insulation.* By meeting these objectives, the following sub-question and accompanying four detailed questions from the methodology have been answered:

1. *What can be learnt from the implementation and execution of the retrofitted EWI at the Arbed I case study dwellings, which can be carried forward to improve future installations through other activities, such as the Green Deal?*
    a. *Did the technical solutions implemented have an effect on the quality of the installations?*
    b. *Did the method of execution have an effect on the quality of the installations?*
    c. *Did the quality of the installations have an effect on the reductions of visible heat loss?*

d. *Do any of the lessons learnt have any implications for other initiatives, such as the Green Deal?*

Throughout the construction quality results set out in Chapter Five above, there were several repetitive findings. The most significant finding is the level of thermal bridging that has occurred. Whilst there appeared to be an overall reduction in heat loss through the whole facade at each of the case study dwellings where pre-retrofit and post-retrofit thermographic surveys were undertaken, there were significant thermal bridges identified in the detailed thermal images. Some of these thermal bridges were anticipated from analysis of the photographs and observed technical details. However, a number of the thermal bridges only became apparent from the thermograms, for example at internal corner junctions and around service entry points. In addition, there are repeated occurrences where apparent inadequate weather protection of the EWI has been identified. Furthermore, there appears to be a correlation between some of the likely causes of the thermal bridging and inadequate weather protection of the EWI. In many instances these issues appear to be caused by one or more of the following:

- Poor workmanship and execution quality on site;
- Poor planning and lack of preparation through preliminary surveys, which led to inappropriate technical design solutions being implemented on site.

Patterson (2012) identified that some occurrences of poor workmanship can be attributed to the shortage in available skilled labour. However, as presented in Chapter Two the evidence from the photographs, observed technical details and thermal images, combined with the argument for adequate preliminary surveys, indicates that there was a clear lack of preparation and planning by the principal contractor and external project manager, as per the design and build contract. In addition, this lack of planning and preparation could have also contributed to the poor workmanship and thus demonstrates how these issues are interlinked. Evidence of these issues includes:

1. New fascia boards being cut too short on site with gaps left between the verge board and fascia board or not long enough to provide adequate weather protection to the EWI fitted to the gable wall. (see Figures 23, 28, 29 and 31)
2. Leaving gaps between the top of the EWI and the roof tiles on the gable wall so old render finish can still be seen, resulting in sub-standard finish and thus appearance. (see Figure 19)
3. Overlapping the capping profile at corner junctions, rather than using proprietary corner junction caps, which results in a sub-standard finish, as well as potentially providing a path for water ingress through capillary action. (see Figures 26 and 27)
4. New gutters not fitted accurately. A dramatic drop in level of the gutter is not required and an indication of a serious lack of care by the installer. (see Figure 21)
5. New drip bead above single storey roof abutment was fitted above level of old drip bead so old render can still be seen, which has resulted in a sub-standard finish and thus appearance. (see Figure 33)
6. Existing gutter not being removed before EWI was installed. Instead the EWI was cut around the end of the gutter. Leaving the gutter embedded in the EWI will mean that when it needs replacing, which is inevitably going

to be before the end of the EWI's life, this will damage the EWI. This has resulted in a sub-standard finish and thus appearance. (see Figure 25)

7. Changing the slope direction of an existing sill during rendering process so that rainwater pools next to the window frame and then penetrates behind the EWI. (see Figures 43 and 45)
8. Gaps between EWI boards due to not being cut straight, the surface not being flat or the requirement for the joining of two types of materials (Phenolic and XPS). Whist the latter was anticipated from the production of the technical details, the former two issues were not expected. These gaps have resulted in thermal bridges occurring in the EWI (see Figures 39, 47, and 49)

The following points constitute evidence of issues which can be specifically attributed to poor planning and preparation:

9. Not replacing a fascia board where it was obviously needed. At one of the dwellings an old window feature had been removed to allow the EWI to be installed. However, as the fascia had been cut around the window feature this resulted in a large gap being left for water ingress and thus penetration of the EWI and substrate. (see Figure 30)
10. At least two of the dwellings had new windows immediately prior to the retrofitted EWI being installed. However, no thought was given to ensure that there was subsequently enough space for the EWI to be returned at the reveals of the openings. Instead like for like frame thicknesses were installed so the reveals were not insulated; thus leaving residual thermal bridges. (see Figure 10)

11. In several of the dwellings with rear annexes there are windows in the external walls, which are at a right angle to the annexe external wall. Due to a lack of adequate preliminary surveys by the principle contractor and external project manager at the design stage, it was not realised that there was not enough space for the EWI to be installed without impeding the occupant to be able to open the window afterwards. As a result large areas of external wall were left without any insulation and thus large thermal bridges. (see Figures 12, 16, 18 and 24)
12. Due to all the dwellings having flush eaves (no roof overhang), a pre-coated aluminium trim or capping profile was used to provide weatherproofing for the top of the EWI. However, due to the proximity of the gutters and downpipe connections, sections of the capping profile had to be cut around these, which have left the EWI vulnerable to water ingress. (see Figures 28 and 31)
13. The final finishing coat was not applied to one dwelling due to the proximity of the telecommunications junction box located on the pavement in front of the dwelling. As a result, there is a large area of EWI that is vulnerable to the weather. (see Figure 34)
14. Where there are garden walls abutting the external walls at some of the dwellings, large thermal bridges have been created. There is also the potential opportunity for water ingress at these locations too. These are particularly apparent in the thermal images which illustrate the gaps between the EWI and the garden wall. (see Figures 48 and 59)

There are also other significant issues that were identified as a result of evaluating the constriction quality of the retrofitted EWI. At three of the critical junctions evaluated using the technical details, the methods of installation were not consistent with the manufacturers' recommendations and thus there could be a risk of invalidating the protection provided by the BBA Certificate. Both the two sill details and the pavement to external wall junction were not implemented as set out in the drawings provided to the housing association by the manufacturer (see Figures 37 to 39 in section 5.2.2 compared to Figures 4 to 6 in Appendix XIV). However, from the thermal images (for example, Figures 71 and 81) it would appear that the approach taken for the second window sill detail and the pavement to external wall junction has improved the overall thermal performance and reduced the opportunities for thermal bridging compared to the manufacturers recommended approach (see below for further discussion). Nevertheless, by not following the recommended installation methods there is a possibility that any issues will not be covered by the warranty.

The first of the two approaches to the window sill junctions was to retain the projection and 'look' of the stone sill (as shown in Figure 38). The primary driver for this approach was aesthetics and not thermal performance. As a result a thermal bridge was created above and below the sills, which is consistent with what was anticipated from reviewing the photographs and producing the technical details; these were then confirmed after analysing the thermal images (see Figures 45, 47, 56, 66 and 67).The second of the two approaches to the window sill junction was to cut off the projecting part of the stone sill, fit a new uPVC sill on top and fit the EWI up to this new sill (as shown in Figure 38). According to one of the housing associations, this approach was not endorsed by the local authority's planning department; this was due to aesthetic reasons. However, this approach appears to be a better solution from a thermal performance perspective when reviewed in the thermal images (see Figures 72, 73, 74, 81 and 83), despite not being anticipated from the photographs and technical details (see Figures 18 and 38).

The approach taken at the plinth of the external walls was to install EWI, rather than leave the area without any insulation as set out in the manufacturers details (as shown in Figure 6 in Appendix XIV). The EWI product used in this location was XPS. However, one of the housing associations opted for using a reduced thickness of XPS compared to the Phenolic, despite the thermal resistance being lower. Therefore, the thermal performance of the two materials is not consistent. This is evident in the relevant thermal images, which show this area of the external walls (see Figures 47, 56, 63, 65 and 66). The other housing association opted for an increased thickness in XPS compared to the Phenolic and this appears to have provided a consistent thermal performance (see Figures 71, 76, 81 and 84).

The final significant issue identified was the use of the capping profile to protect the top of the EWI. This method was used at the eaves due to there being no roof overhang to provide weather protection for the EWI. However, this method results in a residual thermal bridge being created due to the position that the capping profile was fitted, which was under the fascia board. As set out in Chapter Five, dwellings built with this method of construction the ceiling is likely to be at the same level or above the fascia (as shown in Figure 35). In addition, there is a significant risk of water penetration between the fascia board and the capping profile due to the shape and thus poor design. If water penetrates at this point, there is a further significant risk of it travelling down behind the EWI and potentially getting trapped.

Water ingress can have a serious negative effect with certain retrofitted EWI products. Phenolic insulation, which is the EWI used above the plinth level of the external walls at all of the case study dwellings, is one of the EWI products which are affected by water penetration. Where water ingress can penetrate the EWI, this will reduce the thermal performance, potentially to lower levels than before, which completely defeats the purpose of the EWI. The increased thermal conductivity and thus reduced thermal resistance, displayed as bright pink and blue patterns in these thermal images are consistent with the occupier's claim that water has got behind the EWI as a result of the pooling on the first floor window sill. The case study dwelling shown in these thermal images had to have the EWI removed and replaced. This is not a straightforward activity, particularly when the EWI has been installed as part of a whole-street approach as the boards overlap across neighbouring dwellings. These overlaps are an essential part of achieving continuity of the insulation and thus reduce opportunities for thermal bridging at party walls, as well as achieving the economies of scale that can be accomplished using this whole-street approach.

As set out in Chapter Two, a strong emphasis is placed on reducing thermal bridging wherever possible due to the impact that this has on the overall thermal performance of the building. It was further discussed that the unintended consequences resulting from thermal bridging are likely to be damp and mould forming on colder surfaces inside a dwelling where thermal bridging has occurred. However, collecting evidence to this effect is beyond the scope of this doctoral research project and therefore recommended as part of further work below. Nevertheless, the evidence set out in this thesis supports the need for further research and has contributed to the STBA's 'Responsible Retrofit' report by May and Rye (2012). The main focus of this report was to set out the case for further research into the consequences of retrofitting traditionally built walls with modern insulation materials. As a result the DECC have funded an extensive research project, which is being implemented by the BRE.

To return to the objective and research questions set out at the start of this section, based on the key findings discussed here it is concluded that the technical solutions implemented and the method of execution <u>do</u> have an effect on the quality of the installations. In addition, the quality of the installations <u>does</u> have an effect on the reductions of visible heat loss through the external walls. Furthermore, the lessons learnt about retrofitting EWI to existing dwellings, which are set out in this doctoral research project, should be utilised to good effect and thus have implications for other initiatives, such as the Green Deal. Finally, it is anticipated that the construction quality of the retrofitted EWI is likely to have an impact on the energy performance of the case study dwellings. However, this cannot be determined without a detailed discussion of the energy performance data that was collected as part of this doctoral research project.

## 6.2 Key findings from the energy performance data

This section discusses the key findings from the energy performance data (energy consumption, costs and occupant thermal comfort perceptions and behaviour), which seeks to meet objectives three and four of this doctoral research project. To recap, objective three is: *To assess the energy and carbon emission reductions together with the cost effectiveness of retrofitting external wall insulation at the Arbed I case study dwellings and identify any relationship to post-retrofit occupant thermal comfort perceptions and behaviour.* Objective four is: *To determine the value of and need for empirical energy consumption data to confirm the energy performance of traditional dwellings that have received retrofitted external wall insulation.* By meeting these objectives, the following sub-questions (two to four) and accompanying detailed questions from the methodology have been answered:

2. *Has the retrofitted EWI resulted in reduced energy consumption and thus carbon emissions at the Arbed I case study dwellings?*
   a *What are the actual annual energy use and carbon emissions, per square meter of floor area, before and after the EWI was installed?*
   b *Has the retrofitted EWI contributed to the Welsh Government's target of reducing carbon emissions by 3% per annum?*
3. *Is retrofitting EWI cost effective?*
   a *How much did the EWI installations cost per dwelling?*
   b *Do the energy savings cover the capital costs of the EWI, based on available energy prices?*

*4. Are occupant thermal comfort perceptions and behaviour consistent with energy consumption and cost-effectiveness results at the Arbed I case study dwellings?*

   a *How do occupants behave towards energy consumption since the retrofitted EWI was installed?*
   b *How do occupant thermal comfort perceptions correlate with energy consumption and costs?*

The first set of energy performance data set out in Chapter Five was the results of the occupant surveys, which recorded the occupant's thermal comfort perceptions and behaviour towards energy use since having the EWI retrofitted. The answers to the first two questions presented some interesting results. Occupants at 71% of the case study dwellings felt that their home was warmer since the EWI was installed and 67% stated that they had not increased the internal temperature inside the dwelling. Whilst it is recognised that 2011 was the second warmest year on record, as set out by DECC (2012b), the behaviour of the occupants and thus reasons given for not increasing the internal temperature were stated as: trying to save money on the heating bill; and the home not feeling as cold inside. The latter reason being the most common; this corresponds with the external weather conditions. However, as part of the analysis of energy consumption and carbon emissions, heating degree days were used to normalise the data to take account of and thus compensate for the external weather conditions.

Nevertheless, due the mild winter it would be expected that occupants would realise a significant reduction in their energy consumption compared to the previous year before the EWI was retrofitted. Albeit, the occupants at the case study dwellings were in fuel poverty (otherwise they would not have been eligible for the improvements through Arbed I) and therefore not realising any energy savings would be consistent with the research discussed in Chapter Two. This research found that occupants in fuel poverty did not realise any energy savings after energy efficiency retrofits were undertaken due to their dwellings being under heated and thus the rebound effect had occurred. These findings also support other research discussed in Chapter Two; this stated that 80% of occupants do not heat their homes to the levels given for standard occupancy

(21°C in living rooms and 18°C in bedrooms), which are the basis for calculations for complying with the Green Deal's Golden Rule.

The second set of energy performance data in Chapter Five were the energy consumption and carbon emissions from 12 Arbed I case study dwellings. This final number of case study dwellings is half the number for which consent was given by the occupants to collect data direct from their supplier. As set out in Chapter Five, the reasons for this is due to either the energy company not responding to requests for the data or incorrect information being provided by the occupants. Predominantly the latter was as a result of the occupant stating the wrong supplier. It could be argued that if an occupant is not aware of their supplier then it is unlikely that being conscious about energy consumption is not significant to them.

The most significant findings from the energy consumption data are that only three of the 12 case study dwellings realised savings greater than 20%, with one of these being over 40%. Two further case study dwellings realised savings of between 10% and 20% and three others up to 10%. The remaining four case dwellings saw an increase in their energy consumption in the 12 months after the retrofitted EWI was installed. To drill down into these findings further, the occupants at the three dwellings which realised the greatest savings (over 20%) were the only three that were either not sure or did not feel that their home was warmer since the EWI was installed. The occupants at the remaining nine dwellings all stated that they felt their home was warmer since having the EWI installed.

In terms of behaviour towards energy use, only one occupant stated that they had increased the internal air temperature since the retrofitted EWI was installed and their resulting post-retrofit energy consumption reduced by 13%. To add more detail about this case study, the occupancy pattern at this dwelling was continuous at both the pre-retrofit and post-retrofit stages. However, occupants at three of the case study dwellings did not know if they had increased the internal air temperature and they had varying post-retrofit energy consumption: one dwelling saw a reduction of 5% and the occupancy pattern of this dwelling also reduced, along with the number of occupants reducing from two to one; the second saw an increase in 13% and the occupancy pattern increased from partial to continuous; and the third was the dwelling that saw the biggest reduction of 44%, however there was no change in the occupancy pattern. To confirm, the number of occupants at the latter two dwellings did not change during the 12 month post-retrofit period.

At the remaining eight dwellings, the occupants stated they had not increased the internal air temperature since the retrofitted EWI was installed and the number of occupants did not changed between the pre-retrofit and post-retrofit stages. However, three of these eight case study dwellings saw an increase in their energy consumption by 5-6% and none of the occupancy patterns changed between pre-retrofit and post-retrofit stages. Whilst the occupants at the remaining five case study dwellings saw a reduction in their energy consumption of 4%, 5%, 17%, 21% and 23%, the occupancy pattern only reduced at one of these dwellings. Overall it appears that the occupancy pattern at the dwellings did not have a significant effect on the energy consumption at the case study dwellings. Nevertheless, it appears that there is a correlation between thermal comfort perceptions and energy consumption with the greatest savings (over 20%) only being realised by the occupants which stated they did not feel that their home was warmer.

The third and final set of energy performance data was collected to assess the cost-effectiveness of the retrofitted EWI at 10 of the case study dwellings. To confirm, these are the same 10 case study dwellings as the first 10 where energy consumption data was also collected and analysed. From the 10 case study dwellings, only one occupant saw a reduction in their energy bills and this was the dwelling where a 44% energy consumption reduction was realised. The other nine dwellings saw between 5% and 20% increase on their energy bills compared to before the EWI was installed. The reason for this is due to the increased energy costs imposed by the energy suppliers during the 12 months after the EWI was installed.

Most significantly, from the three dwellings where the occupants did not feel that their home was warmer, as well as not or not knowingly increased the internal air temperature, which indicates that the rebound effect has not occurred, and having the most significant reduction in energy consumption (over 20%), only one realised a reduction in their energy bills and therefore was alleviated out of fuel poverty. The other nine case study dwellings remained in fuel poverty. Therefore, retrofitting EWI does not appear to assist with alleviating occupants out of fuel poverty, chiefly due to increasing energy costs, which can primarily be attributed to climate change mitigating legislation and resulting policy implementation. In addition, the cost-effectiveness assessment included a basic payback cost analysis for the retrofitted EWI. Due to the limited data, this assessment was only undertaken for three of the case study dwellings. Moreover, pre-retrofit energy costs had to be used as the post-retrofit figures resulted in no payback at all.

Therefore, based on pre-retrofit energy costs the payback results were 89 years, 414 years and never, which were all beyond the life expectancy of the EWI system. Based on these results, it can be determined that EWI will not work under the rules of the Green Deal, at least not without either or a combination of significant reductions of the costs of installing EWI or energy costs. This supports the rationale for EWI to primarily be installed through ECO, which was discussed in Chapter Two. However, as also discussed in Chapter Two, this is likely to lead to continuous energy price increases so that energy companies can cover the costs of ECO, which will subsequently increase the payback further and most significantly increase levels of fuel poverty, rather than result in reductions. It can therefore be argued that retrofitted EWI should be installed through other funding schemes, which do not impact on consumer energy bills, such as the Welsh Government's Arbed scheme.

A final key finding, which has been identified as part of the energy performance assessments for this doctoral research project is the recognition for the reasons why there is no benchmark for energy use in existing dwellings, based on occupancy. During the early stages of this doctoral research project it was anticipated that there would be sufficient case studies to commence the process of establishing this type of benchmark. However, due to the many reasons, as set out throughout this thesis, such as willingness of the occupants and inconsistency with the data, it has not been possible to make this contribution. Nevertheless, collectively, the analysis of the findings from this doctoral research project set out in this thesis have made an original and significant contribution to knowledge to field of retrofitting EWI to traditional dwellings in south west Wales, particularly where they are located in high exposure to wind driven rain similar to Swansea.

## 6.3 Contribution to knowledge

This doctoral research project has collected empirical data from individual case study dwellings. Collectively, these make up a single case study evaluation of retrofitted external wall insulation installed through Arbed I in Swansea. This case study makes a contribution to knowledge by filling some of the gaps in knowledge about the effectiveness of retrofitted EWI at traditional dwellings in south west Wales. The gaps in knowledge that this doctoral research project has contributed to filling are:

1. **A methodology for simultaneously obtaining empirical data about the construction quality and energy performance of traditional dwellings receiving retrofitted EWI;**
2. **A methodology for assessing the construction quality of retrofitted EWI, which can be used as part of undertaking the quality control process for future installations**;
3. **Empirical baseline energy performance data for traditional dwellings in south west Wales;**
4. **An EWI retrofit case study, which provides simultaneous empirical construction quality and energy performance data from traditional dwellings in south west Wales, which also documents what can go wrong on site, along with the lessons learnt.**

The following aspects of this doctoral research project are original and/or significant:

- The bringing together of photographs, as-built technical details and thermal images to assess a large scale retrofit scheme in single geographical area. As part of this, to have a combination of photographs, an as-built technical detail and thermal images of the same construction detail of retrofitted EWI.
- The use of technical details at the post-retrofit EWI assessment stage. Generally, technical details are only produced at the design stage.
- The use of thermography to look at specific technical details at the post-retrofit EWI stage. Generally, post-retrofit thermal images of EWI only focus upon the whole facade.

## 6.4 Limitations

In summary of the limitations set out in Chapter One, the case study dwellings were limited to those that are located in Swansea, south west Wales and which received retrofitted EWI funded by the Arbed I scheme. In addition, data collection was limited by: the time, resources and budget dictated for this doctoral research project; the skills of the author of this thesis; and the response rate and accuracy of the information provided by the occupants of the case study dwellings. However, despite these limitations, this doctoral research project has been able to make a significant contribution to knowledge to the field of retrofitted EWI, which is an important intervention for working towards climate change targets locally, nationally and internationally.

## 6.5 Further work

1. As a priority, further research should be undertaken to verify the extent to which the construction quality impacted on the energy and carbon emission savings. This could be achieved through a similar study to this doctoral research project where construction quality and energy performance data is collected from dwellings where the retrofitted EWI has been installed with high execution quality and all avoidable thermal bridging has been negated.

2. Whilst energy consumption and thus carbon emission savings, as well as fuel poverty alleviation do not appear to be positive outputs from retrofitting EWI at traditional dwellings in deprived areas of Wales, there could be wider social benefits in the form of savings to the NHS. As discussed in Chapter Two, 'cold' homes are a category one hazard under the housing health and safety rating system and therefore pose a significant risk to the health of occupants. Therefore, this hazard imposes a cost to the NHS that could be reduced through retrofitting EWI. However, this further research needs to establish if breathable insulation reduces the likelihood of damp and mould growth, which could induce health problems for the occupants and thus counteract the benefits of improved thermal comfort for occupants in fuel poverty.

3. Further research should be undertaken to explore contradictory recommendations from the manufacturer. For example, the manufacturer recommends a 75mm gap above a roof abutment and yet not where a garden wall joins an external wall. Furthermore, the manufacturer did not

recommend that these gaps are filled with an alternative material, such as expanding foam, to reduce the likelihood of thermal bridging in these locations of external wall.

## 6.6 Recommendations

Building on the discussions of further work in section 6.5 above, this section lists the recommendations from this doctoral research project:

1. EWI should only be installed where thermal bridging can be avoided until the long-term effects of introducing these are established. Whilst this list is not exhaustive, EWI should only be installed where:
    a. Reveals can be insulated. Where windows and doors are to be replaced at the same time, smaller frames should be fitted to allow the reveals to be insulated.
    b. There is sufficient roof overhang to protect the top of the EWI. If the dwelling has flush eaves then the roof should be extended to provide an overhang to protect the top of the EWI.
    c. There is no obstruction in front of the external wall to prevent the EWI retrofit process from being completed in accordance with the manufacturer's instructions. For example, there should be sufficient space to fit the insulation and apply every layer of the render finish.
2. The methodology used to assess the construction quality of the retrofitted EWI for this doctoral research project should be utilised as a method of undertaking the routine quality control process for all installations.

3. Thermographic images of thermal bridges should be used as part of the training material of installers to illustrate the effects of not ensuring the continuity of retrofitted EWI.
4. A further study is undertaken using the methodology set out in this doctoral research project where the retrofitted EWI has been installed using high standards of execution and thus achieved good quality installations without avoidable thermal bridging to establish if this is the cause of the poor energy performance at the case study dwellings, as set out in this thesis.
5. An area based retrofit scheme should be undertaken at traditional dwellings in Swansea which uses breathable EWI. The same methodology, which was used for this doctoral research project to evaluate the construction quality and energy performance should be utilised to enable a comparison to be undertaken.
6. Following on from Recommendations 4 and 5 above, all of the dwellings should be re-evaluated, preferably every 12 months to establish the long-term implications of the retrofitted EWI. These could include damp and mould growth caused by thermal bridging, as well as assessing levels of fuel poverty.
7. On the basis that the energy performance results in this doctoral research project are an indication that the rebound effect has occurred, which is consistent with previous research (as set out in Chapter Two), and therefore occupants are now achieving satisfactory levels of thermal comfort, retrofitting EWI at dwellings where occupants are in fuel poverty should:

a. be explored as a health policy agenda item, rather than a carbon emissions policy agenda, on the basis that the dwellings will no longer be a category one hazard on the housing health and safety rating system; <u>and</u>

b. use breathable insulation materials to prevent:

   i. damp and mould growth being induced and thus introduce further demands on the NHS; and

   ii. an increase in overall carbon emissions as a result of the embodied carbon in the insulation materials added to the negligible carbon emission savings from reduced energy consumption.

## Chapter summary

The purpose of this chapter was to discuss the findings from the data collected as part of this doctoral research project. Commencing with a summary of the key gaps in knowledge that were identified in Chapter Two to provide the motivation for this doctoral research project, as well as an overview of the rationale for the methodology taken, as set out in Chapters Three and Four, the main focus of this chapter was a discussion of the key findings from the construction quality data and the energy performance data. This was followed by: the contributions to knowledge that have been made from this doctoral research project; a summary of the limitation; a list of further work that could be considered as a follow-on from this doctoral research project; and the recommendations for future retrofitted EWI projects, based on the findings from this doctoral research project.

For the construction quality of the retrofitted EWI, the key findings were that poor workmanship and execution quality on site, along with poor planning and lack of preparation through preliminary surveys, all contributed to the level of thermal bridging and inadequate weather protection that was apparent at the case study dwellings. Additionally, the thermal bridging identified was due to not installing the EWI at the reveals of openings, the use of a capping profile at the eaves and leaving unnecessary gaps, for example at junctions with other building elements. Furthermore, in some instances, the inadequate weather protection was due to the inappropriate use of the capping profile.

For the energy performance, the key findings were that the rebound effect appears to have occurred in the majority of the case study dwellings; this is demonstrated by the fact that the only three dwellings that saw a greater than 20% reduction in the energy consumption were where the occupants stated that their home did not or they did not know if their home felt warmer since the EWI was installed. Nevertheless, due to the increases in energy costs after the EWI was installed only one occupant saw an actual reduction in their energy bill. Furthermore, as a result the payback is greater than the life expectancy of the EWI system and therefore will not work under the rules of the Green Deal. Therefore, these findings support the need for EWI to be installed through ECO. However, due to the impact that this scheme has on energy prices, it was concluded that this is likely to lead to an increase in fuel poverty, rather than a reduction, which is one of the main purposes of retrofitting EWI. It is anticipated that the implementation of the further work and recommendations, also set out in this chapter, will contribute to overcoming many of these issues. These are supported by the conclusions from this doctoral research project.

# Chapter 7: Conclusions

# Chapter 7: Conclusions

This chapter sets out the conclusions of this doctoral research project. These conclusions have been determined from the analysis of the data collected at the case study dwellings provided by two housing associations in Swansea, south west Wales. The case study dwellings received retrofitted EWI, which was installed through the Welsh Government's Arbed I scheme. Commencing with a recap of the aim and objectives of this doctoral research project, this is followed by the conclusions, which make a significant and original contribution to knowledge.

### *Aim*

To investigate the link between the construction quality of retrofitted external wall insulation and the resulting impact on energy efficiency for existing dwellings in Swansea.

### *Objectives*

1. To appraise the implementation and execution of retrofitted external wall insulation at the Arbed I case study dwellings, to determine the effects on the quality of the installations.
2. To determine the value of and the need for non-invasive investigation techniques to confirm the construction quality and thermal integrity of retrofitted external wall insulation.
3. To assess the energy and carbon emission reductions together with the cost effectiveness of retrofitting external wall insulation at the Arbed I case study dwellings and identify any relationship to post-retrofit occupant thermal comfort perceptions and behaviour.

4. To determine the value of and need for empirical energy consumption data to confirm the energy performance of traditional dwellings that have received retrofitted external wall insulation.

***Conclusions***

I. Neither the surveyors, designers nor the installers of the retrofitted EWI demonstrated the knowledge and understanding necessary to deliver an installation of an adequate standard to realise any of the expected benefits of improved thermal performance.

II. The construction quality assessments demonstrate the importance of good quality execution on site, as well as the value of quality control on site during the installation process of retrofitted EWI.

III. The measured energy savings were not significant and it was not cost effective to install the retrofitted EWI at the case study dwellings. However, due to the limitations identified through meeting objective one, it is not possible to conclude that this is due to the EWI being ineffective.

IV. As with modelled data (for example, rdSAP), empirical energy performance data could also give misleading results about the impact of retrofitted EWI. This research has demonstrated that in order to verify energy and carbon savings and payback of retrofitted EWI, the quality of the design and execution needs to be assessed concurrently.

V. To achieve the standards set out in the Building Regulations by following the recommendations set out in Approved Document L1B, it can be determined that achieving the technical feasibility of retrofitting EWI is a prerequisite to the economic feasibility.

VI. Funding initiatives and schemes, such as Arbed, are a good way (and probably the best way) to fund retrofitted EWI in the domestic sector as they do not impact on energy bills and thus contribute to the alleviation of fuel poverty. Conversely installing retrofitted EWI through initiatives such as ECO could be counterproductive.

VII. For the Green Deal and ECO, the findings from this research are equally significant. If EWI is installed through the Green Deal or ECO, it is imperative that the design and execution are of good quality and avoid thermal bridging to avert any questions over the resulting energy performance. To re-cap, under the Green Deal the savings are expected to cover repayments if the capital costs of installing the EWI. However, EWI is more likely to be installed through ECO. Nevertheless, if EWI is installed through ECO then not realising the energy savings will mean that the energy companies will not meet their carbon emission reduction targets. Not meeting these targets results in penalties, usually financial, being issued to the energy company. The energy companies will then need to recoup this money and the most likely way they will do this is to put up the cost of energy for the consumer.

VIII. Qualitative thermographic surveys can be undertaken in warmer weather (outside recommended environmental conditions) for post-retrofit surveys to identify thermal bridging. However, this does not apply to whole house heat loss comparisons.

IX. Using triangulated data from photographs, as-built technical details and qualitative external thermographic surveys provides a non-invasive and robust method of verifying the occurrence of thermal bridging at dwellings which have received retrofitted EWI.

# References

# References


APT. 2011. *Checklist of items/conditions prior to our arrival on site to undertake a Thermographic Test.* [online] Available at: http://www.airpressuretesting.net/thermographic_checklist.php [Accessed June 22 2011].

Association for the Conservation of Energy. 2011. *Scaling the Solid Wall*. London: ACE.

Association of Energy Conscious Builders. 2011. *Customers – Who Will Get What? Comparison to the Green Deal and Energy Company Obligation Consultation November 2011*. Llandysul: AECB.

Bangor University. 2010. *About Knowledge Economy Skills Scholarships at Bangor University.* [online] Available from: http://www.bangor.ac.uk/kess/ [Accessed December 22 2010].

Baxter, J. 2008. *Welsh Housing Quality Standard.* Cardiff: National Assembly for Wales.

Boardman, B. 2007. *Home Truths: A low carbon strategy to reduce UK housing emissions by 80% by 2050.* Oxford: Environmental Change Institute.

BERR. 2008a. *Meeting the Energy Challenge – A White Paper on Nuclear Power*. Norwich: HMSO.

BERR. 2008b. *The UK Fuel Poverty Strategy – 6th Annual Progress Report*. London: Defra.

Buildings Performance Institute Europe. 2011. *Europe's buildings under the microscope – A country-by-country review of the energy performance of buildings*. Belgium: BPIE.

Building Research Establishment. 2002. *Thermal Insulation: avoiding risks*. Watford: Construction Research Communication.

BRE. 2003. *Good Practice Guide 155: Energy efficient refurbishment of existing housing*. (s.l.): Energy Saving Trust.

BRE. 2011. Quick facts: Developing a green refurb strategy for social housing. *Building 4 Change* [online] March 30. Available from: http://www.building4change.com/page.jsp?id=721 [Accessed April 28 2011].

Bryman, A. 2008. *Social Research Methods*. Oxford: Oxford University Press.

Burberry, P. 1997. *Environment and Services.* Eighth Edition. Essex: Pearson Education Limited.

Carbon Trust. 2013. *Conversion Factors.* [online] Available from: http://www.carbontrust.com/resources/guides/carbon-footprinting-and-reporting/conversion-factors. [Accessed: January 15 2014]

Caunt, R. 2009. *Welsh Housing Statistics 2008.* Cardiff: Local Government Data Unit Wales.

Chartered Institute of Housing. 2007. *Building a Greener Future: Towards Zero Carbon Development – CIH's Response to the Consultation paper*. Coventry: Chartered Institute of Housing.

Chartered Institution of Building Services Engineers, The. 2000. *Testing Buildings for Air Leakage – TM23*. London: CIBSE.

CIBSE. 2006. *Degree-days: theory and application TM41: 2006*. London: CIBSE.

Chudley, R., Greeno, R. 2005. *Construction Technology*. Fourth Edition. Harlow: Pearson Education Limited.

City and County of Swansea. 2011. *Welsh Index of Multiple Deprivation 2008 (Revised 2011).* Swansea: City and County of Swansea.

City and County of Swansea (2011), *online air quality & meteorological readings in Swansea*. [online] Available from:

http://www.swansea.airqualitydata.com/cgi-bin/reporting.cgi [Accessed July 11 2013].

City and County of Swansea (2013), *online air quality & meteorological readings in Swansea*. [online] Available from: http://www.swansea.airqualitydata.com/cgi-bin/reporting.cgi [Accessed July 11 2013].

*Climate Change Act* 2008. London: HMSO.

Coastal Housing Group. 2010. *Coastal Housing Group.* [online] Available from: http://www.coastalhousing.co.uk/Pages/default.aspx [Accessed December 22 2010].

Cooper, I., Palmer, J. 2012. *Insulation and thermal storage materials: Expert Panel Meeting 13 February 2012.* London: DCLG.

Construction Products Association. 2010. *An introduction to low carbon domestic refurbishment*. London: Construction Products Association.

Coyne, R. 2012. The Community Green Deal: A model for area-wide delivery of housing retrofit to benefit whole communities. [online] In: *Retrofit 2012*. Salford, January 24-26 2012. Available from: http://www.salford.ac.uk/__data/assets/pdf_file/0008/142469/091-Coyne.pdf [Accessed: January 30 2012].

Davidson, M., Nicol, S., Roys, M., Baeumont, A. 2011. *The cost of poor housing in Wales*. Berkshire: IHS BRE Press.

Decent and Safe Homes. 2007. *Housing Health and Safety Rating System: quick guide*. [online] Available from: http://www.eastmidlandsdash.org.uk/docs/HHSRS-Overview.pdf [Accessed March 16 2011].

Deurinck, M., Saelens, D., Roels, S. 2011. The impact of physical rebound effects on the heat losses in a retrofitted dwelling. *9th Nordic Symposium on*

*Building Physics - NSB 2011*. Tampere University of Technology, May 29 – June 2 2011, Tampere: Tampere University of Technology, pp. 1339-1346.

DCLG (Department for Communities and Local Government). 2006. *Review of Sustainability of Existing Buildings – The Energy Efficiency of Dwellings – Initial Analysis*. Yorkshire: DCLG.

DCLG. 2006b. A *Decent Home: Definition and guidance for implementation*. London: DCLG Publications.

DCLG. 2007a. *Building a Greener Future: policy statement.* London: Department for Communities and Local Government.

DCLG. 2007b. *Accredited Construction Details.* West Yorkshire: DCLG Publications.

DCLG. 2008a. *Existing Housing Stock and Climate Change*. Communities and Local Government Committee Seventh Report of Session 2007-08. London: TSO.

DCLG. 2008b. *Existing Housing Stock and Climate Change*. Communities and Local Government Committee Seventh Report of Session 2007-08, Volume II. London: TSO.

DECC. 2010a. *The Green Deal – A summary of the Government's proposals*. London: DECC.

DECC. 2010b. *Digest of UK Energy Statistics 2010*. London: TSO.

DECC. 2010c. *Energy consumption in the UK: domestic data table 2010 update*. London: DECC.

DECC. 2010d. *Warm Homes, Greener Homes*. London: DECC.

DECC. 2011a. *The Green Deal and Energy Company Obligation Impact Assessment*. London: DECC.

DECC. 2011b. *The Green Deal and Energy Company Obligation Impact Assessment*. London: DECC.

DECC. 2012. *Green Deal Provider Guidance.* London: DECC.

Defra. 2007. *UK Energy Efficiency Action Plan*. London: Defra.

DTI. 2005. *Energy – It's impact on the environment and society*. London: HMSO.

DTI. 2007. *Meeting the Energy Challenge – A white Paper on Energy*. London: HMSO.

Energy Saving Trust. 2000. *Post-construction testing – a professional's guide to testing housing for energy efficiency*. London: EST.

EST. 2005a. *Post-construction testing – a professional's guide to testing housing for energy efficiency*. London: EST.

EST. 2005b. *GBG224 – Improving airtightness in dwellings*. London: EST.

EST. 2006. *CE 184: Practical refurbishment of solid-walled houses*. London: EST.

EST. 2007. *Energy-efficient refurbishment of existing housing*. London: EST.

EST. 2008a. *CE17 – Internal wall insulation in existing housing – a guide for specifiers and contractors*. London: EST.

EST. 2008b. *CE298 – Monitoring energy and carbon performance in new homes*. London: EST.

EST. 2009. *Evaluating energy and carbon performance in the 'Retrofit for the Future' demonstrator projects – Version* 2. (s.l.): EST.

EST. 2010a. *CE309: Sustainable Refurbishment.* London: EST.

EST. 2010b. *F and G Banded Homes in Great Britain – Research into Costs and Treatment*. London: EST.

EST. 2011. Existing Homes Alliance Cymru. *Pre-1919 homes in Wales*. [presentation] March 24. Cardiff: Energy Savings Trust.

EST and BSRIA. 2012. Retro-Expo. *Retrofit for the Future Preliminary results of Testing and Monitoring.* [seminar] October 30. Birmingham: LG Arena.

Energy Reporter. No date. *How is it measured*. [online] Available from: http://www.energyreporter.co.uk/energy-performance-certificates-liverpool/how-is-an-epc-measured [Accessed March 16 2011].

Energy Solutions. 2011. *Cost Effective Retrofit Solutions for Solid Wall Properties*. London: Energy Solutions.

English Heritage. 2007. *Understanding SAP ratings for historic and traditional homes*. London: English Heritage.

English Heritage. 2010a. *Energy Efficiency in Historic Buildings – Insulating Solid Walls*. London: English Heritage.

English Heritage. 2010b. *Energy Efficiency and Historic Buildings: Application of Part L of the Building Regulations to historic and traditionally constructed buildings*. London: English Heritage.

European Union. 2011. *Energy 2020: A strategy for competitive, sustainable and secure energy*. Luxembourg: Publications Office of the European Union.

European Parliament and the Council of the European Union, The. 2010. *DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings*. Brussels: Official Journal of the European Union.

Existing Homes Alliance. 2010. *Key policies for accelerating low carbon retrofit in the existing domestic building stock*. (s.l.): Existing Homes Alliance.

Faulkner, R. 2013. *Advanced Thermography Training.* [workshop] February 20. Emsworth: iRed.

Federal Facilities Council. 2001. *Learning from our buildings*. Washington D.C: National Academy Press.

Garbutt, J. 2008. Insulation Considerations. In: Hall, K. *Green building bible Volume 1*. Llandysul: Green Building Press, pp. 210-213.

Gething, B. 2010. *Design for future climate: Opportunities for adaptation in the built environment.* Swindon: Technology Strategy Board.

Gleeson, C., Yang, J., Lloyd-Jones, T. 2011. *European Retrofit Network: Retrofitting Evaluation Methodology Report.* London: University of Westminster.

Green Building Council. 2008. *Carbon Reductions in Existing Homes – Introduction to the Project*. London: Green Building Council.

H. M. Government. 2002. *Good Practice Guide 310: Degree days for energy management – a practical introduction.* (s.l): (s.n.)

H. M. Government. 2006. *Climate Change: The UK Programme 2006*. London: HMSO.

H.M. Government. 2010a. *Approved Document L1B – The Building Regulations 2000*. London: RIBA Enterprises Ltd.

H.M. Government. 2010b. *Approved Document L1A – The Building Regulations 2000*. London: RIBA Enterprises Ltd.

Hamilton, A. 2002. *HOPE – Home Questionnaire*. (s.l.): BRE.

Hansen, J. Sato, M. Kharecha, P. Beerling, D. Masson-Delmotte, V. Pagani, M. Raymo, M. Royer, D. L. Zachos, J. C. 2007. Target Atmospheric CO2: Where Should Humanity Aim? *The Open Atmospheric Science Journal* [online] 2 2008, pp. 217-231. Available from: http://www.bentham.org/open/toascj/articles/V002/217TOASCJ.pdf [Accessed December 27 2010].

Hart, J.M. 1991. *A practical guide to infra-red thermography for building surveys.* Watford: BRE.

Herbert, T., Mackellow, N. 2010. *Insulating those on the lowest incomes from fuel price rises*. In: Anon. *Evidence.* London: Citizens Advice Bureau.

Herring, H., Roy, R. 2007. Technological innovation, energy efficient design and the rebound effect. *Technovation*, 27(4), pp. 194–203.

Hirsch, D., Preston, I., White, V. 2011. *Understanding fuel expenditure: Fuel poverty and spending on fuel*. Bristol: Centre for Sustainable Energy.

Hong, S., Gilbertson, J., Oreszczyn, T., Green, G., Ridley, I. 2009. A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. London: University College London.

Hopper, J., Littlewood, J., Geens, A., Karani, G., Counsell, J., Thomas, A. 2011a. Developing a methodology for monitoring and evaluating improvements to existing dwellings in deprived areas of Wales. *World Sustainable Building Conference.* Helsinki, October 18-21 2011, Finland: Finnish Association of Civil Engineers RIL and VTT Technical Research Centre of Finland, pp. 184-186.

Hopper, J. Littlewood, J. R. Geens, A. Karani, G. Counsell, J. Thomas, A. 2011b. Improving existing deprived dwellings in Wales: Monitoring and evaluating thermal performance. In: Egbu, C., Sutrisna, M., Underwood, J., Arif, M., Aziz, Z. ed. *10th International Post Graduate Research Conference*. The University of Salford, 14-15 September, Salford: The University of Salford, pp. 162-173.

Hopper, J., Littlewood, J., Geens, A., Karani, G., Counsell, J., Evans, N., Thomas, A. 2012a. Assessing the execution of retrofitted external wall insulation for pre-1919 dwellings in Swansea (UK). [online] In: *Retrofit 2012*. Salford, January 24-26 2012. Available from: http://www.salford.ac.uk/__data/assets/pdf_file/0006/142377/011-Hopper.pdf.

Hopper, J., Littlewood, J., Taylor, T., Counsell, J., Thomas, A., Karani, G., Geens, A., Evans, N. 2012b. Assessing retrofitted external wall insulation using infrared thermography. *Structural Survey*, 30 (3) pp. 232-244.

Hopper, J. 2012c. *Evaluating the installation of retrofitted external wall insulation*. [online] London: Chartered Institute of Architectural Technologists. Available from: http://www.ciat.org.uk/en/awards/student-awards/student-awardreport/ previous-winners.cfm.

Hopper, J. 2013. Assessing Retrofitted External Wall Insulation. In: Emmitt, S. ed. *Architectural Technology Research and Practice*. West Sussex: John Wiley and Sons in association with the Chartered Institute of Architectural Technologists, pp. 177-191.

HouseMark. 2008. *The Welsh Housing Quality Standard: Revised Guidance for Social Landlords on Interpretation and Achievement of the Welsh Housing Quality Standard*. Cardiff: Welsh Assembly Government.

Howarth, S. 2010. *Living in Wales 2008 – Housing Health and Safety Rating System*. Cardiff: Statistics for Wales.

Howarth, S. 2011. *Dwelling Stock Estimates, 2009-10*. Cardiff: Statistics for Wales.

Immendoerfer, A., Houh, C., Andrews, A., Mathias, A. 2008. *Fit for the Future: The Green Homes Retrofit Manual – Technical Supplement*. London: Housing Corporation.

Infrared Training Center. 2010. *Thermography Level 1 Course Manual.* Sweden: Infrared Training Center.

Institute for Sustainability. 2012. *Retrofit insights: perspectives for an emerging industry*. London: Institute for Sustainability.

Intergovernmental Panel on Climate Change. 2007a. Summary for Policymakers. IPCC Fourth Assessment Report: Climate Change 2007: Synthesis Report.

Intergovernmental Panel on Climate Change. 2007b. Human and Natural Drivers of Climate Change. IPCC Fourth Assessment Report: Climate Change 2007: Working Group I: The Physical Science Basis.

IEA. 2010. *World Energy Outlook 2010.* France: IEA

Jackel, Z. 2013. *Delivering and Funding Housing Retrofit: A Review of Community Models*. Arup and Institute for Sustainability.

Janda, K., 2009. Buildings Don't Use Energy: People Do. In: Demer, C., Potvin, A. *26th Conference on Passive and Low Energy Architecture.* Les Presses de l'Université Laval, 22-24 June, Quebec City, Canada, pp 22-27.

Killip, G. 2008. *Building a Greener Britain – Transforming the UK's Existing Housing Stock.* London: Environmental Change Institute, University of Oxford.

King, C. 2011. Existing Homes Alliance Cymru. *The issues with refurbishment of solid walls*. [presentation] March 24. Cardiff: Energy Savings Trust.

King, C. 2013. Constructing Excellence Wales. *Responsible Retrofit*. [Seminar] March 19. Swansea: Constructing Excellence Wales.

King, C., Weeks. C. 2010. *Sustainable Refurbishment of Non-Traditional Housing and Pre-1920's Solid Wall Housing*. Watford: IHS BRE Press.

Knights, C., Potter, N. 2007. *Air tightness testing for new dwellings*. Berkshire: BSRIA.

Leaman, A. 2003. *Post-Occupancy Evaluation*. (s.l.): Building Use Studies.

Leaman, A., Stevenson, F. and Boardass, B. 2010. Building evaluation: practice and principles. *Building Research and Information,* 38 (5), pp. 564-577.

Lo, T.Y., Choi, K.T.W. 2004. Building defects diagnosis by infrared thermography. *Structural Survey,* 22 (5), pp. 259-263.

Lomas, J., Stevenson, F. 2010. *Monitoring Guide for Carbon Emissions, Energy and Water Use*. Warrington: Homes and Communities Agency.

Love, J. *Mapping the impact of changes in occupant heating behaviour on space heating energy use as a result of UK domestic retrofit*. [online] In:

*Retrofit 2012*. Salford, January 24-26 2012. Available from: http://www.salford.ac.uk/__data/assets/pdf_file/0005/142385/023-Love.pdf

Maby, C. 2011. Existing Homes Alliance Cymru. *Target 2050 countdown to a low carbon future*. [presentation] June 17. Cardiff: Energy Savings Trust.

May, N. 2005. *Breathability: The key to building performance.* Buckinghamshire: Natural Building Technologies.

May, N. 2012. SPAB Technical Panel. *Responsible Retrofit for Traditional Buildings Research Project*. [presentation] June 12. London: SPAB.

May, N. and Rye, C. 2012. *Responsible Retrofit of Traditional Buildings*. London: Sustainable Traditional Buildings Alliance.

Morgan, N. 2009. *Retrofit For The Future Phase 1 Technical And Energy Modelling Guidance Notes V1.0.* Swindon: TSB.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T. P., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R. A. 2009. *UK Climate Projections Science Report: Climate change projections.* Exeter: Met Office Hadley Centre.

National Audit Office. 2008. *Programmes to reduce household energy consumption*. London: The Stationary Office.

National Audit Office. 2010. *The Decent Homes Programme*. London: The Stationary Office.

National House Building Council. 2011. *How occupants behave and interact with their homes: The impact on energy use, comfort, control and satisfaction*. Milton Keynes: NHBC Foundation.

National Housing Federation. 2012. *Approaches to engaging households with their energy use*. London: National Housing Federation.

Nicol, S., Roys, M., Davidson, M., Summers, C., Ormandy, D., Ambrose, P. 2010. *Quantifying the cost of poor housing*. Watford: BRE.

Oppenheim, A. N. 1992. *Questionnaire Design, Interviewing and Attitude Measurement*. London: Continuum.

Palmer, J., Campbell, R., Boardman, B., Saunders, J. 2005. *Fuel Poverty Research Centre Scoping Study*. Oxford: Environmental Change Institute.

Palmer, J. Cooper, I. 2011. *Great Britain's housing energy fact file*. London: DECC.

Patterson, J. 2012. *Arbed 1 Scheme Evaluation of the Warm Wales Programme*. Cardiff: Welsh School of Architecture.

Pearson, C. 2002. *Thermal Imaging of Building Fabric – A best practice guide for continuous insulation.* Berkshire: BSRIA.

Pearson, C. 2011. *Thermal Imaging of Building Fabric.* Berkshire: BSRIA.

Pearson, C., Seaman, A. 2003. *Condition-based maintenance using non-destructive testing.* Berkshire: BSRIA.

Phlorum. 2012. *Insulating a street: Brighton case study.* Brighton: BBM Sustainable Design.

Preiser, W. 2002. The Evolution of Post-Occupancy Evaluation: Toward Building Performance and Universal Design Evaluation. *Learning from Our Buildings: A State-of-the-Practice Summary of Post-Occupancy Evaluation.* Washington, pp 9-22.

Proverbs, D. Gameson, R. 2008. Case study research. In: Knight, A and Ruddock, L. Ed. *Advanced research methods in the built environment.* Oxford: Blackwell Publishing Ltd, pp. 99-110.

Randall, C. 2011. *Housing*. Newport (South Wales): Office for National Statistics.

Rhodes, M., Knights, I., Agyenim, F. 2007. Categorising the existing Welsh housing stock in terms of heating and cooling demand and thermal storage capacity. In: *2nd PALENC Conference and 28th AIVC Conference on Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century.* Crete Island, Greece, September, pp. 818-824.

Roys, M., Davidson, M., Nicol, S. 2010. *The Real Cost of Poor Housing.* Watford: BRE.

Ruyssevelt, P. 2012. Retro-Expo. *Introduction to Retrofit for the Future.* [seminar] October 30. Birmingham: LG Arena.

Rye, C. and Hubbard, D. 2012. Retro-Expo. *The performance of traditional buildings.* [seminar] October 31. Birmingham: LG Arena.

Sandell, Z. 2013. Boost given to solid wall insulation following planning rules change. *Sustainable Homes* [online] March 22. Available from: http://www.sustainablehomes.co.uk/blog/bid/114343/Boost-given-to-solid-wall-insulation-following-planning-rules-change?utm_source=hubspot_email_marketing&utm_medium=email&utm_content=8042218&_hsenc=p2ANqtz-_wDvsTZwIT-jKhpQtBrfgRDvknnIkiRfrczdZvcIO0i0JiTepsWTFYQTFJysdMGLS4ajD9tz2egMQ-mLH0v3jBdsPOIA&_hsmi=8042218 [Accessed April 25 2013].

Sheridan, L. 2009. *Developing a standardised methodology for post-occupancy evaluation of recently built housing*. (s.l.): The Scottish Government.

Shore. J. 2008. Choosing materials. In: Hall, K. *Green building bible Volume 1*. Llandysul: Green Building Press, pp. 195-198.

Snell, J., Spring. R. 2002. *Non-destructive Testing of Building Envelope Systems Using Infrared Thermography*. Vermont: Inframation.

Stafford, A., Gorse, C., Shoa, L. 2011. *The Retrofit Challenge: Delivering Low Carbon Buildings*. Birmingham: Centre for Low Carbon Futures, University of Birmingham.

Stern, N. 2006. *Stern Review on The Economics of Climate Change.* London: H M Treasury.

Stevenson, F. 2010. TSB Building Performance Evaluation Briefing. *Post-occupancy evaluation: analysing residents needs, satisfaction and behaviour for design feedback*. [workshop] September 22. (s.l.): Oxford Brookes University.

Stevenson, F. and Leaman, A. 2010. Evaluating housing performance in relation to human behaviour: new challenges. *Building Research & Information*, 38 (5), pp. 437-441.

Stirling, C. 2001. *Good Building Guide 44: Insulating masonry cavity walls*. Watford: BRE.

Sustainable Development Commission. 2006. *Stock take: delivering improvements in existing housing*. London: SDC.

Technology Strategy Board. No date. *Low energy building database*. [online] Available from: http://www.retrofitforthefuture.org/ [Accessed April 27 2011].

TSB. 2010. *Building Performance Evaluation, Domestic Buildings – Guidance for Project Execution*. Version3. Swindon: TSB.

TSB. 2013. *Scaling up retrofit of the nation's homes*. [online leaflet] Available from: https://www.h2020uk.org/documents/1524978/1866952/Scaling+up+retrofit+of+the+nation's+homes++-+Competition+Brief/af8e005a-6448-4617-93a2-cc497018e2d9 [Accessed April 20 2013].

Thomsen, K. E., Rose, J. 2009. *Analysis of Execution Quality Related to Thermal Bridges.* Denmark: Danish Building Research Institute.

Thorpe, D. 2010. *Sustainable Home Refurbishment*. London: Earthscan.

Vesma. 2013. *20-year average heating degree days for the UK*. [online] Available from: http://vesma.com/ddd/20year07.htm. [Accessed: July 17 2013].

Ward, T. 2006. *Information Paper 1/06: Assessing the effects of thermal bridging at junctions and around openings.* Watford: BRE.

Welsh Assembly Government. 2005. *Welsh Housing Statistics 2004.* [online] Available from: http://wales.gov.uk/topics/statistics/publications/publication-archive/whs2004/?lang=en. [Accessed January 15 2011].

Welsh Assembly Government. 2008a. *Welsh Index of Multiple Deprivation (WIMD) 2008 Summary Report*. Cardiff: Welsh Assembly Government.

Welsh Assembly Government. 2008b. *Statistical Geographies.* [online] Available from: http:statswales.wales.gov.uk/DDS03000_080400_statisticalgeographies_eng [Accessed August 12 2010]. (No longer available)

Welsh Assembly Government. 2010a. *Background*. [online] Available from: http://wales.gov.uk/topics/environmentcountryside/energy/efficiency/arbed/background/?skip=1&lang=en. [Accessed August 20 2010].

Welsh Assembly Government. 2010b. *Phase 1 Projects*. [online] Available from: http://wales.gov.uk/topics/environmentcountryside/energy/efficiency/arbed/phase1projects/?lang=en. [Accessed August 20 2010].

Welsh Assembly Government. 2010c. *Arbed – Strategic energy performance investment programme*. [online] http://wales.gov.uk/topics/environmentcountryside/energy/efficiency/arbed/?lang=en [Accessed August 20 2010].

Welsh Assembly Government. 2010d. *Fuel Poverty Strategy 2010*. Cardiff: Welsh Assembly Government.

Welsh Government, 2010e. *A Low Carbon Revolution: Wales Energy Policy Statement.* Cardiff: Welsh Assembly Government.

Welsh Economy Research Unit. 2011. *The Housing Associations of Wales: Measuring the Impact IV*. Cardiff: Cardiff University.

Welsh Government. 2012. *Social Landlords' Performance in Achieving the Welsh Housing Quality Standard (Revised)*. (s.l.): Welsh Government.

Wingfield, J., Johnston, D., Miles-Shenton, D., Bell, M. 2010. *Whole House Heat Loss Test Method (Coheating)*. Leeds: Leeds Metropolitan University.

Woosey, S. 2012. *Evaluation of arbed Phase One: A report into the impacts of the first phase of the Welsh Government's arbed programme between 2011 and 2012*. Mold: Eco Centre Wales.

Yergin, D. 2006. Ensuring Energy Security. *Foreign Affairs*, 85 (2) March/April, pp. 69-82.

Zimring, C. 2010. *Facility Performance Evaluation (FPE)*. [online] National Institute of Building Services. Available from: http://www.wbdg.org/resources/fpe.php [Accessed April 27 2011].

Zimring, C. Reizenstein, J. 1980. Post-Occupancy Evaluation. *Environment and Behavior,* 12 (4) December, pp. 429-450.