The measured energy efficiency and thermal environment of a UK house retrofitted with internal wall insulation

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The measured energy efficiency and thermal environment of a UK house retrofitted with internal wall insulation

by

Victoria Tink

Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy of Loughborough University

(June 2018)

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Abstract

Approximately 30% of the UK’s housing stock is comprised of older, solid wall buildings. Solid walls have no cavity and were built without insulation; therefore these buildings have high heat loss, can be uncomfortable for occupants throughout the winter and require an above-average amount of energy to heat. Solid wall buildings can be made more energy efficient by retrofitting internal wall insulation (IWI). However, there is little empirical evidence on how much energy can be saved by insulating solid wall buildings and there are concerns that internal wall insulation could lead to overheating in the summer.

This thesis reports measured results obtained from a unique facility comprised of a matched pair of unoccupied, solid wall, semi-detached houses. In the winter of 2015 one house of the pair was fitted with internal wall insulation then both houses had their thermal performance measured to see how differently they behaved. Measuring the thermal performance was the process of measuring the wall U-values, the whole house heat transfer coefficient and the whole house airtightness of the original and insulated houses. Both houses were then monitored in the winter of 2015, monitoring was the process of measuring the houses’ energy demand while using synthetic occupancy to create normal occupancy conditions. In the summer of 2015 indoor temperatures were monitored in the houses to assess overheating. The monitoring was done firstly to see how differently an insulated and an uninsulated house perform under normal operating conditions: with the blinds open through the day and the windows closed. Secondly, a mitigation strategy was applied to reduce high indoor operative temperatures in the houses, which involved closing the blinds in the day to reduce solar gains and opening the windows at night to purge warm air from the houses.

The original solid walls were measured to have U-values of 1.72 W/m²K, while with internal wall insulation the walls had U-values of 0.21 W/m²K, a reduction of 88%. The house without IWI had a heat transfer coefficient of 238 W/K; this was reduced by 39% to 144 W/K by installing IWI. The monitored data from winter was extrapolated into yearly energy demand; the internally insulated house used 52% less gas than before retrofit. The measured U-values, whole house heat loss and energy demand were all compared to those produced from RdSAP models. The house was found to be more energy efficient than expected in its original state and to continue to use less energy than modelled once insulated. This has important implications for potential carbon savings and calculating pay-back times for retrofit measures.

In summer, operative temperatures in the living room and main bedroom were observed to be higher, by 2.2 °C and 1.5 °C respectively, in the internally insulated house in comparison to the uninsulated house. Both of these rooms overheated according to CIBSE TMS2 criteria; however the tests were conducted during an exceptionally warm period of weather. With the simple mitigation strategy applied the indoor operative temperature in the internally insulated house was reduced to a similar level as observed in the uninsulated house. This demonstrates that any increased overheating risk due to the installation of internal wall insulation can be mitigated through the use of simple, low cost mitigation measures.
This research contributes field-measured evidence gathered under realistic controlled conditions to show that internal wall insulation can significantly reduce the energy demand of a solid wall house; this in turn can reduce greenhouse gas emissions and could help alleviate fuel poverty. Further to this it has been demonstrated that in this archetype and location IWI would cause overheating only in unusually hot weather and that indoor temperatures can be reduced to those found in an uninsulated house through the use of a simple and low cost mitigation strategy. It is concluded that IWI can provide a comfortable indoor environment, and that overheating should not be considered a barrier to the uptake of IWI in the UK.
Acknowledgements

This work was made possible by the EPSRC funding for the London-Loughborough Centre for Doctoral Training in Energy Demand (LoLo): grant EP/H009612/1. The author would like to thank the owner of the test houses used in this study; the work would not have been possible without the houses being generously provided for two years.

Studying for a PhD for many people can be a lonely journey, however for me this was not the case due to the endless support I received. I would like to thank my primary supervisor, Dr David Allinson, for his enthusiasm for the project, his infinite kindness and limitless encouragement. I would also like to thank my second supervisor, Prof Dennis Loveday, for his insightful thoughts and feedback over the years. And lastly my thanks go to my third supervisor, Dr Stephen Porritt, for the many hours of work spent creating a worthy test facility together.

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I would like to acknowledge everyone at LoLo for making it an excellent environment to work in and a place to share ideas, particularly Ozlem, Selin, Argyris, Chad, Kate and Sofie. I would like to thank Prof Kevin Lomas for creating LoLo, and for giving me the opportunity to study with so many great people. I would also like to thank Karen Holmes for her help with everything outside of the thesis and for her friendship.

I would like to say a special thanks to Dan for all of your love, help and always being so understanding. Your words of encouragement always mean so much and your patience has made this journey a joy. Lastly and most importantly, I would like to thank my mum. I could not have produced a PhD thesis without your endless support. I can’t thank you for each and every thing you have done for me. So I’ll thank you for teaching me to read, write and think for myself; look how it turned out.
# Table of Contents

1 **Introduction** .................................................................................................................. 1

1.1 **Research Context** ..................................................................................................... 1

   1.1.1 Climate change ........................................................................................................ 1
   1.1.2 The UK housing stock ............................................................................................ 1
   1.1.3 Improving the thermal performance of UK houses .............................................. 2
   1.1.4 The performance gap .............................................................................................. 3
   1.1.5 The potential for summer overheating ..................................................................... 3

1.2 **Research Aim and Objectives** .................................................................................. 4

1.3 **Thesis Overview** ....................................................................................................... 5

2 **Literature Review** ......................................................................................................... 18

2.1 **Solid wall dwelling characteristics** ........................................................................ 18

   2.1.1 Materials and construction ..................................................................................... 18
   2.1.2 Thermal performance of houses with solid walls .................................................. 20

2.2 **Retrofit of solid wall dwellings** ................................................................................ 22

   2.2.1 Solid wall insulation ............................................................................................... 22
   2.2.2 Incentives to retrofit with IWI ............................................................................... 23
   2.2.3 Barriers to retrofit with IWI .................................................................................... 25
   2.2.4 Types of internal wall insulation ............................................................................ 26

2.3 **Thermal performance of houses with solid wall insulation** ...................................... 28

2.4 **Measuring homes** ..................................................................................................... 30

   2.4.1 Energy efficiency and thermal performance measurement studies ..................... 30
   2.4.2 Overheating measurement studies ......................................................................... 33
   2.4.3 The performance gap .............................................................................................. 34

2.5 **Overheating in dwellings** ........................................................................................ 38

   2.5.1 Defining overheating ............................................................................................. 39
   2.5.2 Causes of overheating ............................................................................................ 40
   2.5.3 Consequences of overheating ............................................................................... 43
   2.5.4 Preventing overheating .......................................................................................... 44

2.6 **Chapter Summary** .................................................................................................... 46

3 **Research design and methods** ..................................................................................... 48

3.1 **Introduction** .............................................................................................................. 48

3.2 **Research design** ....................................................................................................... 48
3.2.1 A case study using test houses ................................................................. 48
3.2.2 Measuring thermal performance ............................................................... 49
3.2.3 In-situ monitoring in winter and summer ................................................... 49
3.2.4 Comparing measurements with models ..................................................... 50

3.3 Test Houses ..................................................................................................... 50
3.3.1 Description of the test houses .................................................................... 50
3.3.2 Geometry of the test houses ....................................................................... 52
3.3.3 Preparing the houses for testing ................................................................. 53
3.3.4 Internal wall insulation .............................................................................. 53
3.3.5 Thicknesses of the external walls ............................................................... 54

3.4 Methods for measuring thermal performance .................................................. 55
3.4.1 Air permeability measurement ................................................................... 55
3.4.2 Thermal transmittance (U-value) measurement ............................................ 56
3.4.3 Whole house heat transfer measurement .................................................... 57
3.4.4 Infra-red thermography ............................................................................. 57

3.5 Method for monitoring the test houses in winter .............................................. 58
3.5.1 Winter monitoring tests ............................................................................ 58
3.5.2 Winter synthetic occupancy profile ............................................................ 58
3.5.3 Winter internal gains ............................................................................... 60
3.5.4 Central heating profile ............................................................................. 63
3.5.5 Winter blind and window use .................................................................... 63

3.6 Method for monitoring the test houses in summer ............................................ 64
3.6.1 Summer monitoring tests ......................................................................... 64
3.6.2 Summer synthetic occupancy profiles ......................................................... 65
3.6.3 Summer internal gains ............................................................................. 66
3.6.4 Summer blind and window use .................................................................. 68

3.7 Analysing monitoring data ............................................................................ 68
3.7.1 Side-by-side data analysis of winter monitoring data .................................... 69
3.7.2 Side-by-side data analysis of summer monitoring data .................................. 70
3.7.3 Assessing overheating .............................................................................. 70
3.7.4 Methods for normalising and extrapolating measured data ....................... 73
3.7.5 Degree-Days modelling .......................................................................... 75
3.7.6 Linear regression modelling ..................................................................... 78
3.7.7 Validating models ..................................................................................... 81
List of Figures

Figure 3-1: The test houses (Top image: before renovation, Bottom image: prepared for testing) .......................... 51
Figure 3-2: Floor plans of the test houses ........................................................................................................... 52
Figure 3-3: Internal wall insulation installation, metal frame (left) and phenolic boards (right) .................... 54
Figure 3-4: Winter family of four synthetic occupancy schedules .................................................................... 60
Figure 3-5: Summer elderly couple synthetic occupancy schedules ............................................................... 65
Figure 3-6: Indoor comfort temperature as a function of exponentially weighted running mean outdoor temperature of the previous day (BSI 2007b) ........................................................................ 71
Figure 3-7: Definition of Degree-Days, the average difference between the baseline temperature and the outdoor air temperature ........................................................................................................... 76
Figure 3-8: Data Splitting for model building .................................................................................................. 82
Figure 3-9: Calibration of black globe thermistors (left) and thermistors and thermocouples (right) ........... 90
Figure 3-10: Shielded air temperature sensor ................................................................................................. 91
Figure 3-11: Operative temperature station ..................................................................................................... 92
Figure 3-12: Operative temperature station locations ..................................................................................... 93
Figure 3-13: Surface temperature sensors ..................................................................................................... 93
Figure 3-14: Test Schedule ............................................................................................................................. 95
Figure 4-1: Experimental setup of air permeability test ............................................................................... 97
Figure 4-2: Floor plans with positions of Point U-value measurements ....................................................... 98
Figure 4-3: Thermal images showing inappropriate (left) and appropriate (right) locations to position heat flux sensors ......................................................................................................................... 99
Figure 4-4: Experimental setup of U-value measurement, inside the house (left) and outside the house (right) ........................................................................................................................................... 100
Figure 4-5: Experimental setup of co-heating test .......................................................................................... 101
Figure 4-6: Thermal image of infiltration heat loss from the bay of the left house ........................................ 105
Figure 4-7: Thermal images detailing thermal bridging on test houses ......................................................... 108
Figure 4-8: Thermal image of side-wall heat loss decreasing as the distance from the ground increases ...... 109
Figure 4-9: View of micro-cavities within solid brick walls in the bay window of the right house .............. 110
Figure 4-10: Brick wall on side wall of right house, laid in a Monk bond ...................................................... 111
Figure 4-11: Comparison of data analysis methods for the co-heating test data ........................................ 115
Figure 4-12: Co-heating analysis of Test 1 and 2 using siviour plus regression analysis ........................... 117
Figure 4-13: Indoor temperatures, external temperatures and solar radiation in co-heating tests 1 and 2 .... 118
Figure 4-14: Wind speed and rainfall during co-heating tests .................................................................... 119
Figure 5-1: Winter Test 1 volumetrically weighted indoor air temperatures, heat consumption, outdoor air temperatures and solar radiation .................................................................................... 123
Figure 5-2: Winter Test 2 volumetrically weighted indoor air temperatures, heat consumption, outdoor air temperatures and solar radiation ............................................................................. 124
Figure 5-3: Cooling curves of five days of Winter Test 2: Left House Insulated ................................................................. 126
Figure 5-4: Degree-days method in the right house .............................................................................................................. 129
Figure 5-5: Residuals from the right house multiple regression models .............................................................................. 132
Figure 5-6: Residuals from the left house regression models ................................................................................................. 134
Figure 6-1: Matched Pair Test Indoor operative temperature, outdoor air temperature and horizontal solar radiation ............................................................................................................................................................ 140
Figure 6-2: Box and whisker plots of living room and main bedroom operative temperature and outdoor air temperature. ............................................................................................................................................................. 142
Figure 6-3: Left House Insulated Test indoor operative temperature, outdoor air temperature and horizontal solar radiation .................................................................................................................................................... 143
Figure 6-4: Mitigation Test Indoor operative temperature, outdoor air temperature and horizontal solar radiation ........................................................................................................................................................................ 146
Figure 6-5: Daily swings in indoor operative temperature ....................................................................................................... 147
Figure 6-6: Indoor operative temperature in the Left House Insulated Test and the Mitigation Test regressed against exponentially weighted outdoor running mean temperature, with boxplots of current and future predicted weather .............................................................................................................................................. 151
List of Tables

Table 2-1: Limiting U-value standards history for England and Wales (W/m².K) (King 2007) ........................................... 20
Table 2-2: Measured U-values of solid wall buildings from UK studies ................................................................. 21
Table 3-1: Brick wall thicknesses .......................................................................................................................... 55
Table 3-2: Winter test configurations ...................................................................................................................... 58
Table 3-3: Heat gains for a family of four occupancy profile ...................................................................................... 62
Table 3-4: Summer test configurations ..................................................................................................................... 65
Table 3-5: Heat gains for an elderly couple occupancy profile .................................................................................... 67
Table 4-1: Measured air permeability ...................................................................................................................... 104
Table 4-2: Calculated air permeability .................................................................................................................... 106
Table 4-3: Measured point U-values ....................................................................................................................... 107
Table 4-4: Calculation of the thermal resistance of a solid brick wall ...................................................................... 110
Table 4-5: Calculation of the thermal resistance of a solid brick wall with micro-cavities ............................................. 112
Table 4-6: Calculation of the thermal resistance of a solid brick wall with 50mm of internal wall insulation applied ....................................................................................................................... 113
Table 4-7: Measured heat transfer coefficients .......................................................................................................... 116
Table 4-8: Measured and calculated whole house heat transfer coefficients ............................................................. 120
Table 5-1: Side-by-side comparison of winter energy demand .................................................................................... 125
Table 5-2: Predicted heat consumption using the degree-days method ................................................................. 128
Table 5-3: Predicted heat consumption for the right house using multiple regression models ............................... 130
Table 5-4: Multiple regression models assumptions for the right house ................................................................. 131
Table 5-5: Linear regression models for the left house .............................................................................................. 133
Table 5-6: Regression models assumptions for the left house ................................................................................... 133
Table 5-7: Annual energy models assumptions for the left house extrapolated from measured data ....................... 134
Table 5-8: Annual heat demand of the left house calculated using RdSAP ............................................................. 135
Table 6-1: Internal gains from synthetic occupancy in summer ................................................................................... 139
Table 6-2: Descriptive statistics of indoor operative temperature, outdoor air temperature and solar radiation in occupied periods ................................................................................................................... 141
Table 6-3: Amount of overheating during each test in occupied hours ................................................................. 144
Table 6-4: Summer regression results ..................................................................................................................... 150
Table 7-1: Differences in measured and modelled energy demand ........................................................................... 157
Table 7-2: Predicted energy demand pre and post retrofit using measured HTCs ...................................................... 159
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ASHRAE</td>
<td>American Society of Heating, Refrigeration and Air-Conditioning Engineers</td>
</tr>
<tr>
<td>ATTMA</td>
<td>Air Tightness Testing &amp; Measurement Association</td>
</tr>
<tr>
<td>BADC</td>
<td>British Atmospheric Database Centre</td>
</tr>
<tr>
<td>BEIS</td>
<td>Department for Business, Energy and Industrial Strategy</td>
</tr>
<tr>
<td>BRE</td>
<td>Building Research Establishment</td>
</tr>
<tr>
<td>BSI</td>
<td>British Standards Institute</td>
</tr>
<tr>
<td>Cat</td>
<td>Category</td>
</tr>
<tr>
<td>CCC</td>
<td>Committee on Climate change</td>
</tr>
<tr>
<td>CIBSE</td>
<td>Chartered Institute of Building Services Engineers</td>
</tr>
<tr>
<td>DCLG</td>
<td>Department for Communities and Local Government</td>
</tr>
<tr>
<td>DECC</td>
<td>Department of Energy and Climate Change</td>
</tr>
<tr>
<td>ECO</td>
<td>Energy Companies Obligation</td>
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<tr>
<td>EFUS</td>
<td>Energy Follow-Up Survey</td>
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<tr>
<td>EHS</td>
<td>English Housing Survey</td>
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<td>EPC</td>
<td>Energy Performance Certificate</td>
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<tr>
<td>EST</td>
<td>Energy Saving Trust</td>
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<td>EWI</td>
<td>External wall insulation</td>
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<tr>
<td>GDP</td>
<td>Gross domestic product</td>
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<tr>
<td>HTC</td>
<td>Heat transfer coefficient</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>IWI</td>
<td>Internal wall insulation</td>
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<tr>
<td>MAD</td>
<td>Mean absolute difference</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>NEED</td>
<td>National Energy Efficiency Data-Framework</td>
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<tr>
<td>OFGEM</td>
<td>Office of Gas and Electricity Markets</td>
</tr>
<tr>
<td>ONS</td>
<td>Office for National Statistics</td>
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<tr>
<td>PHE</td>
<td>Public Health England</td>
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<tr>
<td>PIR</td>
<td>Polyisocyanurate</td>
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<tr>
<td>RdSAP</td>
<td>Reduced data SAP for existing dwellings</td>
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<tr>
<td>SAP</td>
<td>The Government’s Standard Assessment Procedure for Energy Rating of Dwellings</td>
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<tr>
<td>sd</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>SWI</td>
<td>Solid wall insulation</td>
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<tr>
<td>TRV</td>
<td>Thermostatic radiator valve</td>
</tr>
<tr>
<td>TRY</td>
<td>Test reference year</td>
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<tr>
<td>uPVC</td>
<td>Unplasticized polyvinyl chloride</td>
</tr>
<tr>
<td>US</td>
<td>United States of America</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>UKAS</td>
<td>UK’s National Accreditation Body</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>The United Nations Framework Convention on Climate Change</td>
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<tr>
<td>ZCH</td>
<td>Zero Carbon Hub</td>
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1 Introduction

1.1 Research Context

1.1.1 Climate change

The concentration of CO$_2$ and other greenhouse gases in the atmosphere has increased from pre-industrial levels; this is due to the burning of fossil fuels for usable energy (IPCC 2013). This increase in greenhouse gases has resulted in the world’s atmosphere and oceans warming, snow and ice levels reducing, sea levels rising and oceans acidifying (IPCC 2013). These changes impact plant and animal life by changing the availability of food and water and increasing the frequency of extreme weather events such as flooding, cyclones and wildfires (IPCC 2014). Climate change will also affect human life. In Europe, climate change will affect humans through a reduction in water availability, an increase in flooding and extreme heat events, and will lead to economic losses (IPCC 2014).

To limit climate change and its effects, there must be a “substantial and sustained reduction in greenhouse gas emissions” (IPCC 2013). To achieve this reduction countries joined an international treaty: the United Nations Framework Convention on Climate Change (UNFCCC), which has prompted international co-operation through the Kyoto Protocol and the Paris Agreement (The United Nations 2014a). Both of these global initiatives have been ratified by the United Kingdom (The United Nations 2014b; The United Nations 2017).

Under the Kyoto Protocol the UK government committed to a reduction in CO$_2$ emissions of 80% by 2050, compared to 1990 levels (Climate Change Act 2008; The United Nations 2014a). The Climate Change Act of 2008 turned this agreement into policy, in which legally binding five-yearly carbon budgets were also created (Climate Change Act 2008). By 2016, the UK had reduced its CO$_2$ emissions to 42% below 1990 levels (CCC 2017b). The first carbon budget was met, and the UK is projected to outperform on the second and third (CCC 2017a). However, the UK is not on track to meet its fourth carbon budget: a reduction of 51% by 2025 (CCC 2017a).

1.1.2 The UK housing stock

In 2016 29% of the UK’s final energy was consumed in residential buildings; approximately 80% of this energy was used for space and water heating (BEIS 2017b). This energy consumption released 93.2 MtCO$_2$e into the atmosphere, 20% of the UK’s total emissions (CCC 2017b). Between 2002 and 2015, final energy consumption in homes fell by 19% (BEIS 2016). A fall in median energy consumption was recorded in all house types, among all tenures and locations, and with occupants from all socio-demographic backgrounds (BEIS 2017d). The drop was due to a combination of factors including financial pressure brought on by rising energy prices, as well as the impact of energy efficiency measures for houses and appliances (BEIS 2016). However, final energy consumption in dwellings rose by 0.8% in 2016. To meet carbon budgets using the least cost route set out by the Committee for Climate Change (2017b), levels of energy consumption in dwellings must continue to fall.
The UK has one of the oldest and least energy efficient housing stocks in Europe (Boardman et al. 2005). There were 27.7 million dwellings in Great Britain in 2016 (BEIS 2017c). 8.5 million (31%) of these dwellings had solid walls: external walls that have a single mass of material with no cavity (BEIS 2017c). Buildings are rated on their energy performance in the UK using the Standard Assessment Procedure (SAP) (DECC 2013). Solid wall dwellings have poor SAP ratings in comparison to buildings of other wall constructions, such as cavity wall dwellings. In 2014, solid wall properties in England had an average SAP rating of 55, lower than the average housing stock rating of 61 (DCLG 2016d). Additionally, 12.5% of dwellings with solid walls are in the lowest energy efficiency bands: F and G (DCLG 2016d).

The majority of solid wall houses were built before 1919 (Baker 2011), to lower thermal standards than today due to a lack of national building regulations. This means they exhibit high heat loss through walls, have single glazed windows and high rates of ventilation (Roberts 2008; Jones et al. 2013). 29% fail one or more of the Decent Homes Standard criteria (DCLG 2017a), higher than the 19% average for all housing stock; the majority fail on the criteria of insulation and heating measures (Vadodaria et al. 2010).

The rate of housing demolition in England is very low. In 2015-16, 10,420 dwellings were demolished (DCLG 2016e), equating to a yearly removal of just 0.04% of the housing stock. Most of the current housing stock will still be here in 2050 (Power 2008), therefore to meet carbon budgets through the least cost route the existing housing stock must be improved (CCC 2017b).

1.1.3 Improving the thermal performance of UK houses

To improve the thermal performance of solid wall dwellings, measures can be installed including condensing boilers, double glazed windows, and loft insulation, all of which are relatively simple to retrofit (Jones et al. 2013). However, in an uninsulated solid walled house the largest proportion of heat loss occurs through the walls (EST 2014). The installation of solid wall insulation reduces solid wall heat loss; therefore less energy is required to heat the house to the same temperature for occupants.

Solid wall heat loss can be reduced by insulating walls internally or externally. Each method has its own drawbacks and benefits. Internal wall insulation (IWI) can be applied to more buildings because it can be used on many heritage and conservation properties without affecting the façade (Kolaitis et al. 2013). IWI may also be significantly cheaper than external wall insulation: the house protects the materials, so they do not need to be as hard wearing; and there is no access scaffolding required during installation which adds significant expense for external wall insulation (EST 2016; Al-Homoud 2005).

Of the 8.5 million solid wall dwellings in Great Britain at the end of 2016, 718,000 had solid wall insulation applied; 92% of solid wall dwellings remained uninsulated (BEIS 2017c). 31,000 installations of solid wall insulation were completed in 2016 (CCC 2017b). However, this rate is not sufficient. To reduce CO₂ emissions to the level the UK has committed through the least cost method, 2 million solid wall buildings must be insulated by 2030 at a rate of 90,000 a year (CCC 2017b).
1.1.4 The performance gap

Solid wall insulation is effective at saving energy and therefore reducing CO$_2$ emissions (BEIS 2017d). It is believed that, once insulated, solid wall buildings could be more energy efficient than cavity wall buildings (Lowe 2007). However, there is a significant performance gap between the predicted energy performance of houses and what is actually achieved when buildings are retrofitted to make them more energy efficient (Gupta, Gregg, Passmore, et al. 2015; Gupta & Gregg 2016; Hong et al. 2006; Khoury et al. 2016). There is currently very little empirical evidence of the measured thermal performance of solid wall dwellings with internal wall insulation applied (BRE 2014). There is some evidence that IWI can dramatically reduce U-values (Stevens & Bradford 2013; Walker & Pavia 2015) and energy demand (Stevens & Bradford 2013; Gupta & Gregg 2016; DECC 2016a), however there is no evidence of measured whole house thermal performance. This leads to the first research question: what is the improvement in whole house thermal performance of houses with internal wall insulation applied?

Accurate measurements are necessary to understand and close the performance gap between modelled and measured buildings (Butler & Dengel 2013; Jack et al. 2017). Empirical data is required on the effect of installing internal wall insulation in solid wall houses, on their thermal performance and energy demand reduction potential; to ensure that a performance gap does not exist when applying IWI to the building stock, and the aim of CO$_2$ emission reduction is achieved. This lack of empirical data poses the second research question: what are the likely energy and CO$_2$ savings in houses retrofitted with internal wall insulation?

Further to this, there has been little comparison of measured values to standard predictive models such as SAP. Only one study of this type was identified, which was a retrofit of mixed EWI and IWI and it was reported that SAP targets were not met (Gupta & Gregg 2016). There will likely be a performance gap between the measured and modelled performance of dwellings with IWI if poorly predicting models are used and a lack of knowledge on the actual performance of houses with IWI continues. The lack of studies in this area leads to the third research question: is SAP an appropriate tool for assessing the effectiveness of energy efficiency retrofit using IWI?

1.1.5 The potential for summer overheating

There is the potential for unintended consequences to occur due to the installation of internal wall insulation. For example, internal wall insulation could cause overheating in summer. Overheating is when the indoor temperature in a dwelling is too high to provide the occupants with comfort (CIBSE 2013). Overheating does not only cause occupants discomfort; it can also impact their health, sleep quality and productivity (ZCH 2015a).

Several modelling studies have shown that IWI causes an increase in indoor temperatures and increases overheating risk (Porritt et al. 2012; Gupta & Gregg 2013; Mavrogianni et al. 2012; Ji & Webster 2012). Further modelling studies have shown that temperatures can be lowered in UK homes with IWI through the use of sensible mitigation strategies, such as solar shading and sufficient ventilation (Porritt et al. 2012; Mavrogianni
et al. 2014). There have been no measurement studies on the effect of internal wall insulation on indoor temperatures and overheating, nor the effectiveness of mitigation strategies. The inherent uncertainty in modelling calls for more measured data to quantify the overheating risk (DCLG 2012). This uncertainty frames the final two research questions: does internal wall insulation cause overheating in summer once applied; and can simple mitigation measures combat the risk?

To summarise the five research questions above:

Research Question 1: What is the improvement in whole house thermal performance of houses with internal wall insulation applied?

Research Question 2: What are the likely energy and CO₂ savings in houses retrofitted with internal wall insulation?

Research Question 3: Is SAP an appropriate tool for assessing the effectiveness of energy efficiency retrofit using IWI?

Research Question 4: Does internal wall insulation cause overheating in summer once applied?

Research Question 5: Can simple mitigation measures combat the risk of overheating in summer?

1.2 Research Aim and Objectives

The aim of this research is to quantify the impact of retrofitted internal wall insulation on thermal performance, energy demand and summer overheating in UK solid wall dwellings. This will give confidence in estimating the amount of energy demand reduction that can be achieved when retrofitting the UK solid wall housing stock. The research will also offer knowledge on the summer overheating potential and recommendations for providing comfortable summer living environments for occupants in houses with IWI.

The objectives are:

Objective 1: Predict the thermal performance of solid wall houses before and after the installation of internal wall insulation, using simple and widely used models.

Objective 2: Characterise the thermal performance of solid wall houses to quantify the heat losses before and after the installation of internal wall insulation. This will provide data to answer the first research question. By comparing measured heat losses with those predicted in objective 1, it will also help to answer the third research question on whether SAP is an effective tool in assessing retrofit.

Objective 3: Measure the energy demand of solid wall houses before and after the installation of internal wall insulation. The amount of energy saved by installing IWI can then be quantified; answering the second research question. This will also provide further comparison to the models in objective 1, models answering the rest of the third research question.

Objective 4: Measure the overheating risk and the effectiveness of a mitigation strategy in solid wall houses before and after the installation of internal wall insulation. Any possible increase in
overheating risk due to insulating, and any decrease in risk due to mitigating will be quantified, answering the two final research questions.

1.3 Thesis Overview

This chapter has given the broad context for the work and has defined the aim and objectives of the study. Chapter 2: Literature review details the current knowledge on the energy efficiency of solid wall buildings, opportunities and barriers to their retrofit, the performance gap and the causes and consequences of overheating. Chapter 3: Research design and methods describes the research design and gives an overview of the methods used to measure thermal performance, energy demand and summer overheating. This also includes a description of the use of a pair of solid wall houses in which these experiments were conducted. Chapter 4: The impact of IWI on thermal performance addresses objectives 1 and 2 by detailing the predicted and measured air permeabilities, wall U-values and heat transfer coefficients of a solid wall house with and without internal wall insulation applied. Chapter 5: The impact of IWI on space heating energy demand fulfils objective 3 by detailing the amount of energy saved annually in a solid wall house by installing internal wall insulation. Chapter 6: The impact of IWI on summer overheating fulfils objective 4 by detailing the effect of internal wall insulation on indoor temperatures in summer and presents a method for overheating mitigation. Chapter 7: Discussion reviews the study and suggests changes to models to better predict the thermal performance and energy demand of solid wall houses with and without internal wall insulation. The discussion also offers recommendations for the installation of internal wall insulation that will provide comfortable living environments in summer. Chapter 8: Conclusion summarises the work, presents the contributions to knowledge and gives recommendations to stakeholders.
2 Literature Review

The previous chapter provided justification for the research, this chapter provides a more detailed context for the research. The construction method and the materials used in solid wall dwellings are varied (Section 2.1). This results in a varied thermal performance, but with solid wall dwellings performing worse than cavity wall dwellings (Section 2.1). Solid wall dwellings’ thermal performance can be improved by installing solid wall insulation (Section 2.2). Solid wall insulation can be applied internally or externally, with different incentives and barriers to each (Section 2.2). However, dwellings with good thermal performance can be at risk of overheating, improving the thermal of solid wall dwellings could also put them at risk of overheating (Section 2.5). Although overheating is a risk it can be prevented with passive mitigation strategies (Section 2.5).

2.1 Solid wall dwelling characteristics

The UK has an old and energy inefficient housing stock (Boardman et al. 2005). Solid wall houses were the primary method of construction in the 18th and 19th centuries (Vadodaria et al. 2010) and are considered to be a ‘traditional construction’ if they were built prior to 1919 and the materials used are moisture permeable (May & Rye 2012). In 2015 solid wall homes constituted 26.3% English housing stock (DCLG 2017a) and one quarter of the Scottish housing stock (The Scottish Government 2016). Solid wall houses were built to lower thermal standards than houses today. The walls were often constructed from brick, but there is a great variation in materials and wall thicknesses which in turn results in a great variation in thermal conductivity.

2.1.1 Materials and construction

The external wall of a house can be categorised by whether it is solid or cavity wall construction. A solid wall has a single mass of solid material, with no cavity between layers. Solid walls are a traditional construction technique, usually made of moisture permeable materials (May & Rye 2012). Over 80% of pre-1919 dwellings have solid walls (DCLG 2017a), therefore it is possible to use the age band of pre-1919 as a proxy for buildings having solid walls (Baker 2011). People began to experiment in building cavity wall homes from the early 19th century onwards, by the early 20th century most pattern books for houses included examples of cavity walls (Oxley Conservation 2012b). Cavity walls were adopted because they offered greater protection from wind driven rain and they were more economical to build (Oxley Conservation 2012b; Vadodaria et al. 2010). Analysis of 230 houses in Leicester as part of the 4M project revealed that the most typical type of house in Leicester is a solid wall house built between 1920-1944 (Oraiopoulou et al. 2015). There was no immediate step change from solid to cavity wall construction, with many solid wall houses continuing to be built into the 1940’s (Oxley Conservation 2012b).

There is significant variability among solid wall properties; the style, material and construction techniques developed over many centuries (Cook 1983). Prior to the 18th century houses were designed and built by local people with little formal training; these buildings were based around function, local style and the local materials available (Brunskill 1971). These houses therefore vary depending on where they were constructed
(Brunskill 1992; Penoyre & Penoyre 1978). From the mid-18<sup>th</sup> century onwards the trend moved towards houses being built to the style of the day by professional builders (Brunskill 1971; Cook 1983; Potter & Potter 1973).

In England solid wall dwellings are mostly made from bricks. Bricks used in the construction of houses were often typical to the area and were produced to different sizes, permeabilities, hardness (Oxley Conservation 2012a). In a study by Rhee-Duverne and Baker (2013) they identified walls in Berkshire were made from soft, porous, homogenous bricks; whereas in the Midlands and the North of England walls were made from hard, dense bricks, but of uneven quality. Solid brick walls can contain irregular voids, irregular bonding patterns and imbedded wood (Oxley Conservation 2012a). Bricks became more regular with the mass manufacture and transportation of building materials across Britain via rail and canal (Potter & Potter 1973). Large scale building that occurred in the Victorian period in brick produced the solid walled terraces of suburbs in towns that are present today (Potter & Potter 1973; Cook 1983).

Bricks were not the only construction material used to produce houses across the UK, traditionally others include stone, rubble, flint and rammed earth (Oxley Conservation 2012a; Brunskill 1971). In Scotland many traditional solid walls were built from stone (Baker 2011); they walls are not homogenous, they have large stones used on the inside and outside face, and smaller stones in the centre (Baker 2011), this makes them less regular than solid walls built with mass manufactured bricks. There are also examples of solid reinforced concrete solid wall buildings which were produced after the second world war (Gould 1977; Potter & Potter 1973). No data is available on the number of solid wall dwellings of each construction material type i.e. brick, concrete, stone. However material use is closely linked to the location and age of a property, the more recently constructed the more examples of that building type there will be (Brunskill 1971), therefore there are more brick built solid wall homes still in the building stock.

When using bricks, blocks or pieces of stone the materials had to be bonded to one another in order to make a wall. Bonding materials also vary depending on the geographical region and had varying permeabilities and durabilities (Oxley Conservation 2012a). In older properties bonding materials were earth or clay, with lime mortar became prevalent (Oxley Conservation 2012a; Baker 2011).

The external surface of the walls could be left bare, or were concealed for weather proofing or to improve appearance (Brunskill 1971). In the Historic England study into U-values (Rhee-Duverne & Baker 2013) there were examples of houses with painted brick work and cement render, but the majority of homes were left bare. A finish such as paint or lime wash would make little difference to the U-values of a wall, however a layer of significant thickness could make a difference to the U-value. Such finishes include lime render, clay render, sand and cement render and pebble dash.

Walls in UK homes are generally finished internally to give a smooth finish, onto which paint or wallpaper is applied for decoration. In solid wall properties usually bricks are plastered onto directly, sometimes walls are
dry lined with plasterboard, then plastered and occasionally bricks are painted onto directly (Rhee-Duverne & Baker 2013).

A study by the BRE classified solid walls into two categories ‘standard and ‘non-standard’ (Hulme & Doran 2014). Those which were considered to be standard in England were of mass construction, made of brick, and were one header and one stretcher brick thick – resulting in a thickness of roughly 229cm (Hulme & Doran 2014). Once renders and plaster is included a ‘standard’ wall should be less than 330mm thick. Walls of dwellings were built to varying thicknesses, Victorian walls are generally between 100-330 mm thick (Makrodimitri 2010), and most traditional dwellings have walls less than two feet thick (Oxley Conservation 2012a; Brunskill 1971). Walls built in brick were built using various brick patterns (Makrodimitri 2010).

Of the solid wall dwellings in England 21% of them are semi-detached houses, 11% are end-terraces, 30% are mid-terraces, 8% are detached, 4% are bungalows and 26% are flats (DCLG 2017a). 82.4% of all English dwellings are within city centre, urban or suburban areas (DCLG 2013b); 75% of solid wall houses are in urban centres and suburban residential regions (Vadodaria et al. 2010). 30% of all solid wall properties are located in London, whereas only 3% are within the North East, the remaining proportion are evenly distributed across England (Vadodaria et al. 2010).

2.1.2 Thermal performance of houses with solid walls

Solid wall dwellings are still built today and have always been subject to the building regulations of the day. Within England and Wales there has been development of the thermal building standards since the introduction of the conservation of fuel and power in 1965 (King 2007). Therefore solid wall dwellings built from 1965 onwards should comply with the values set out within Table 2-1.

Table 2-1: Limiting U-value standards history for England and Wales (W/m².K) (King 2007)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wall</td>
<td></td>
<td>1.7</td>
<td>1.1</td>
<td>0.7</td>
<td>0.48</td>
<td>0.47</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td></td>
<td>1.5</td>
<td>0.68</td>
<td>0.4</td>
<td>0.26</td>
<td>0.25</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Floor</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.45</td>
<td>0.45</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Windows</td>
<td></td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>3.3</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Solid wall dwellings built before 1965 were built to little or no thermal standards, with high heat loss through the walls, compared to modern buildings. Both the choice of material and the thickness of the wall construction has a significant impact on a solid wall buildings current energy performance (DCLG 2013b). This is because the U-value of the wall is a measure of thermal transmittance, the lower the U-value, the less heat is transmitted, therefore the house retains more heat and it is more energy efficient to achieve the same indoor comfort level.
RdSAP and CIBSE Guide A (DECC 2013; CIBSE 2015a) both state that solid brick walls have a U-value of 2.1 W/m²K; based on a solid brick wall 220mm thick with 13mm of dense plaster. As described in Section 2.1.1, there is significant variation in solid wall materials and construction, therefore a single value is unlikely to be suitable for all constructions (Li et al. 2014). There have been several U-value measurement studies of UK houses with solid wall brick construction, Table 2-2. The table gives both the average U-value and the range or standard deviation in U-values (studies provided one or the other) of each studies sample. This range or standard deviation describes the variation in wall U-values between different houses in each study. The average U-values in all studies are lower than the standard assumed U-value of 2.1 W/m²K. There have been several other studies on the U-values of solid walls such as those by Wright et al. (2012) and Currie et al. (2013), these are not included in Table 2-2. They have been excluded because the studies were of non-standard solid walls made from stone or were significantly thicker than 9 inches.

Due in part to their poorly performing walls, solid wall dwellings have poor energy performance ratings compared to cavity wall constructions (DCLG 2016d), although these are calculated using the wall U-value of 2.1 W/m²K. Dwellings built pre-1919, which are likely to be of solid wall construction, are modelled in The Government’s Standard Assessment Procedure for Energy Rating of Dwellings (SAP) to be most energy inefficient age band of buildings (DCLG 2013b; DCLG 2016c). For a detailed explanation of SAP, see Section 3.8. Despite dwellings built pre-1919 having the lowest average SAP rating (DCLG 2016c), pre-1919 dwellings use only the second largest amount of gas (DECC 2016b), with those built between 1919-1944 consume the most gas. This could be explained by the lower average indoor temperatures found in solid wall dwellings compared to ideal or average temperatures (Oreszczyn et al. 2006; May & Rye 2012).

It is also believed that solid wall buildings they have high air change rates, however a sample of 93 solid wall homes was measured and found to be a median of 10.1 m³/h.m² (Birchall et al. 2011). New build homes must have an air permeability less than 10 m³/h.m² (DCLG 2013a), therefore on average solid walls lose as much heat through air loss as the worst performing new build properties.

Table 2-2: Measured U-values of solid wall buildings from UK studies

<table>
<thead>
<tr>
<th>Author</th>
<th>Number of houses</th>
<th>Average U-value (W/m²K)</th>
<th>Range of U-values (W/m²K)</th>
<th>Standard deviation of U-values (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walker and Pavia (2015)</td>
<td>1</td>
<td>1.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li et al. (2014)</td>
<td>40</td>
<td>1.3</td>
<td>1.32</td>
<td>0.35</td>
</tr>
<tr>
<td>Hulme and Doran (2014)</td>
<td>85</td>
<td>1.57</td>
<td></td>
<td>0.32</td>
</tr>
<tr>
<td>Stevens and Bradford (2013)</td>
<td>93</td>
<td>1.43*</td>
<td>2.53 - 0.36</td>
<td></td>
</tr>
<tr>
<td>and Birchall et. al (2011)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhee-Duverne and Baker (2013)</td>
<td>18</td>
<td>1.4</td>
<td>2.2 – 1.0</td>
<td></td>
</tr>
<tr>
<td>Rye (2012)</td>
<td>11</td>
<td>1.24</td>
<td>2.48 - 0.64</td>
<td></td>
</tr>
</tbody>
</table>

*Indicates median values, other averages are the mean
Solid wall houses have a large exposed amount of thermal mass which offers thermal inertia, creating a more stable internal thermal environment against outdoor temperature spikes (Makrodimitri 2010); this should offer comfort for occupants. However studies have found that solid wall homes tend to be colder in winter than those that are newer or of are other wall types (Oreszczyn et al. 2006); this is likely due to their high heat loss. One study found that the winter indoor temperature in solid wall homes has remained similar for the past 40 years (Vadodaria et al. 2014), with average temperatures in occupied living rooms of 18.7 °C. Another study on indoor temperatures by Kane et al. (2015) analysed mean indoor winter temperatures from 249 houses in Leicester, UK. The average temperature across all houses was 18.5 °C in living rooms and 17.4 °C in bedrooms. Solid wall houses were found to be cooler than the average: 18.0 °C in living rooms, but the same 17.4 °C in bedrooms.

2.2 Retrofit of solid wall dwellings

Legally binding carbon reduction targets (Climate Change Act 2008) mean that UK carbon dioxide emissions must be reduced in all sectors, including the residential sector (CCC 2017b). Energy efficiency measures have contributed to the reduction in final energy consumption in the residential sector by 14% from 2002-2015 (DECC 2016a), however more energy efficiency is required to meet carbon budgets.

Solid wall dwellings can be made more energy efficient by insulating their walls, this will offer the greatest energy saving because this is where the greatest proportion of heat is lost (EST 2014). 807,000 (14%) of England’s solid wall dwellings have solid wall insulation applied. To meet carbon dioxide reduction targets the Committee on Climate Change recommends insulating 2 million solid wall dwellings by 2030. This needs to be completed at a current rate of 90000 per year, in 2016 the rate was 31000 per year (CCC 2017b); the UK is not on track to insulate these dwellings and therefore reduce CO₂ emissions. There are many incentives but also many barriers to the retrofit of solid walls generally and using IWI specifically (sections 2.2.2 and 2.2.3).

Solid wall insulation can be placed internally or externally (section 2.2.1). IWI is the focus of this research because it can be cheaper and less complex to install than EWI and there is little known about its thermal performance. IWI is also the only option to improve the walls of some heritage buildings, it is a necessary alternative to EWI to improve the national stock. IWI can be applied using different methods and using different materials (section 2.2.4). There is little current evidence of the thermal performance of buildings that have IWI installed (section 2.3).

2.2.1 Solid wall insulation

Solid wall insulation (SWI) is applied to solid walls to reduce their rate of heat loss. Solid wall insulation can be applied to the internal face: internal wall insulation (IWI), or to the external face: external wall insulation (EWI). Solid wall insulation is not only applied to solid wall dwellings, but also on other hard-to-treat dwellings. Building external walls with a cavity began in the early Victorian age, therefore there are many older cavity wall properties (Brunskill 1971). The two layers of early cavity walls were often tied together using a brick, and had varying sizes of cavity: some less than 50mm thick (Oxley Conservation 2012b). These would be
considered hard-to-treat cavity walls, unsuitable for cavity fill, and therefore require solid wall insulation (Oxley Conservation 2012b). IWI and EWI can be used together on one house: IWI could be used on the front face of the building to preserve the facade and EWI could be applied to the sides and the back of a building (Lowe 2007).

Solid wall insulation can be installed as a single retrofit measure or as part of a package of whole house retrofit measures (Loveday & Vadodaria 2013; Jones et al. 2013). SWI is most effective when installed as a whole package (Simpson et al. 2016; Loveday & Vadodaria 2013), but can be more appealing to householders retrofit houses in stages (Fawcett 2013). It is possible that householders would choose to install solid wall insulation as a later retrofit measure due to its expense and difficulty; often ‘low hanging fruit’ such as double glazing, condensing boilers, draft stripping and loft insulation would be installed first (Jones et al. 2013). However SWI reduces lifetime CO₂ emissions more by installing solid wall insulation early in the retrofit of a solid wall house (Simpson et al. 2016).

2.2.2 Incentives to retrofit with IW

There are incentives for the retrofit of solid wall houses with solid wall insulation, these are presented first. These incentives are as an alternative to doing nothing: leaving the houses as they are. There are also incentives for the use of internal wall insulation over the use of external wall insulation, these are presented second.

The UK government strives for energy in the UK that is secure, reliable, affordable and clean. Reducing energy demand supports these aims and reduces CO₂ emissions. To reduce UK energy demand the UK’s solid wall housing stock must be made more efficient, or this older stock can be demolished and replaced with new housing. It is thought by Boardman et al. that there should be a targeted demolition program removing a small amount of the worst performing homes (2005). The current rate of demolition of dwellings is very low, a yearly removal of 0.04% of the housing stock (DCLG 2016e). In the year 2016-2017 162,880 dwellings started construction, an increase of 0.7% of the building stock. Neither is sufficient to replace the existing solid wall building stock. Demolition is low, in part, because it is very unpopular: it is disruptive and expensive (Boardman et al. 2005). In addition, building materials are a resource which is wasted through demolition, including the embodied energy and CO₂ emissions required to produce them. 4-8 times less resource is required to refurbish existing stock, compared with building new houses and demolishing the existing stock (Power 2008). The current stock will not be replaced (Power 2008), therefore energy efficiency measures are the necessary path to energy demand and CO₂ reduction (CCC 2017b).

Energy efficiency reduces fuel bills for householders both now (Williams & Gillott 2011), and offers protection against future price rises (DECC 2014b). Energy efficiency also tackles fuel poverty (Hansford 2015; Williams & Gillott 2011; Boardman et al. 2005; Oreszczyn et al. 2006), insulating houses occupied by low income households increases indoor temperatures (Oreszczyn et al. 2006). This increase in indoor temperature improves household comfort, health and wellbeing (Hansford 2015; Williams & Gillott 2011; Oreszczyn et al. 2006).
2006). 29% of solid wall dwellings fail the Decent Homes Standard criteria (DCLG 2017a), mainly due to poor insulation. 10% of solid wall properties also have issues with damp (DCLG 2017a) which can lead to mould growth and poor indoor air quality (Hall et al. 2013). Improving these solid wall dwellings could improve occupant health and reduce winter mortality by increasing indoor temperatures and improving indoor air quality (Boardman et al. 2005; DECC 2014b).

Houses that are in a current state of disrepair or empty can be improved by installing energy efficiency measures such as wall insulation. Older dwellings are also more likely to be unoccupied, which is one cause of them being in disrepair (DCLG 2013b). Improving the fabric reduces maintenance costs for the building and can aid in regenerating neighbourhoods (Hansford 2015). Solid wall homes are more likely to be empty, by improving them it is more likely people will want to occupy them (Ireland 2008). The work to refurbish homes creates jobs in the construction sector (DECC 2014b), and would also contribute to GDP and tax revenues (Hansford 2015).

Internal wall insulation has several benefits over external wall insulation. IWI can be a superior option on high rise buildings, where installation of EWI would be prohibitively difficult and where buildings are too close together to allow for EWI (Kolaitis et al. 2013). There is a significant cost benefit of IWI, it was found to be 50% cheaper than EWI when applied to a range of different building types (EST 2016; Kolaitis et al. 2013; DCLG 2013b); however this is dependent on the work to be done. The Energy Saving Trust quote typical installation costs as £4000 - £13,000 (EST 2016). External wall insulation can be high in cost: £9000 - £25,000, because of the extra alterations to the building such as extending the eaves (EST 2016; Oxley Conservation 2012a). However if external work is required regardless of insulation, for example if the brickwork requires repointing, or render replacing, external may be cost effective (EST 2016). An added expense for EWI is the scaffolding required for installation, whereas this is rarely required for IWI (Oxley Conservation 2012a). A further monetary benefit of IWI is that it can be made more affordable through installing the work in stages, on a room by room basis, which may make it more appealing for householders (EST 2016; Vadodaria et al. 2010). In terms of energy saving there are conflicting arguments, Al-Homoud (2005) comments that under transient heat flow and where the main load is heating in winter, internal placement of insulation is best as this is the point of entry for the heat. However Kolaitis (2013) comments that external placement of insulation offers a larger saving in heat energy demand of 8%.

Within heritage buildings applying internal wall insulation may be the only legal option, because external insulation would destroy the current façade (Historic England 2017; Oxley Conservation 2012a). Buildings can be prevented from being retrofitted with energy efficiency measures due to listing or being within a conservation area. Buildings can be listed to protect them against change or demolition because they are considered to be part of the nation’s heritage due to their architectural or historic importance (Rhee-Duverne & Baker 2013). In 2016 in England there were over 370,000 listed buildings, in Scotland there are over 47,000, in Wales there are over 30,000 and in Northern Ireland there are over 8500 (Historic England 2017; Historic
Environment Scotland 2016; Cadw 2014; Department for Communities 2017). The older a property is the more likely it is to be listed, in England all well preserved buildings built before 1700 are listed and there are very few post WW2 listings (Historic England 2017).

There are different categories of listed buildings, which are slightly different in each country (Historic England 2017; Historic Environment Scotland 2016; Cadw 2014; Department for Communities 2017):

- **Grade I** (England and Wales), Grade A (Scotland and N. Ireland) include buildings of national importance due to historic or architectural reasons.
- **Grade II** (England and Wales), Grade B (Scotland), Grade B+ (N. Ireland) include very special buildings that are possibly nationally important.
- **Grade II** (England and Wales), Grade C (Scotland), Grade B1 and B2 (Northern Ireland) are buildings that are locally important, some imperfection or alteration is acceptable.

A building being listed or within a conservation area does not directly prevent any work, such as the installation of solid wall insulation. However, listed building consent and planning permission must be gained before undertaking any alteration, extension or demolition work (Planning (Listed Buildings and Conservation Areas) Act 1990). Internal wall insulation may be more likely to achieve listed building consent as it does not alter the exterior of the building and therefore does not require planning permission (Oxley Conservation 2012a). However, this is not always the case as the installation can affect plaster cornices, door frames and skirting boards which are likely to be destroyed when removed (Oxley Conservation 2012a). In unlisted buildings and those not within conservation areas there is no need to gain any permission to install external or internal wall insulation (DCLG 2013c).

2.2.3 Barriers to retrofit with IWI

Barriers to the retrofit of solid wall insulation are presented first, followed by the specific barriers of IWI. Expense is a major barrier to the installation of SWI (Jones et al. 2013). The up-front cost may be too expensive for the owners of property; desirable funding mechanisms are needed to encourage the uptake of SWI. Linked to the barrier of expense is the tenure of the property, social housing is the most likely to have solid wall insulation (DCLG 2017b), installed through funding mechanisms such as the Energy Companies Obligation (ECO) available to social housing providers. Owner occupiers lack access to some funding such as the ECO (DECC 2014b). In privately rented dwellings those living in the house, paying the bills and experiencing discomfort are not the people who make the decisions around improvements, so retrofit may not occur. This is being tackled by the government by not allowing the rent of properties with very poor energy efficiency from 2018 (DECC 2014b).

Householders from the CALEBRE study commented that they live in older houses because of their character and architectural features (Vadodaria et al. 2010), it may be unappealing to many to have SWI installed if it would destroy this character. However if this is put into the context of refurbishment or demolition, retrofit could arguably be more appealing. Retrofit is disruptive to the householders (Jones et al. 2013), which they
may not think is worth the benefits gained. Risk for householders may also be a barrier to retrofit, whether this is real or perceived. Poor installations are negative consequences leads to a poor reputation of the industry (Hansford 2015), this in turn prevents householders from retrofitting. Under the Green Deal and ECO installers are obliged to provide a 25 year warrantee on installations of solid wall insulation (DECC 2014b), this reduces risk for householders but increases risk for industry, which could be a barrier for installers.

There are several barriers to the installation of IWI compared to EWI. The installation of IWI can be highly disruptive for occupants living in the house. The room being insulated would need to be cleared while the work was done and there could be significant dust and dirt. EWI offers less disruption internally (Vadodaria et al. 2010), however could have significant delays to delivering the final product due to bad weather (Al-Homoud 2005). Internal fixtures, fittings and services must be removed for the installation of IWI (EST 2016); original features such as skirting board and plaster coving could be damaged when removed, this may be unacceptable if the building is listed or to many home owners who value the period features. Other items such as kitchens and bathrooms would be very difficult to remove and fitted worktops may no longer fit and need to be altered, recommendations are made that insulation works are carried out alongside a planned kitchen or bathroom refit (DCLG 2013b; EST 2016). IWI may not always result in an overall reduction in price compared to EWI if significant work must be done internally (EST 2016). IWI reduces the area of rooms, which many may find unacceptable (Vadodaria et al. 2010; DCLG 2013b; Loucari et al. 2016).

Internal wall insulation has some further risks compared with EWI. Advice from the US Department of Energy is that external should always be used where possible as it presents the least risk and best option thermally, due to having fewer thermal bridges (Straube et al. 2012; Loucari et al. 2016). Thermal bridges can be created by installing insulation internally or externally, but more are created with IWI due to floors and party walls which bridge the insulation (Oxley Conservation 2012a; Kolaitis et al. 2013). Internal wall insulation isolates the indoor air from the external wall mass, whereas EWI does not (Williams & Gillett 2011). This could cause increased overheating due to isolating the thermal mass (Kolaitis et al. 2013; Loucari et al. 2016; Porritt et al. 2012).

The placement of IWI compared with EWI makes the original brick wall colder. If the wall was cold enough this could be an issue as because moist air could condense on the brick (Kolaitis et al. 2013; Loucari et al. 2016), this interstitial condensation could then run onto the timber floor and joists causing timber rot (Oxley Conservation 2012a; Wright et al. 2012; Morelli et al. 2012). Another issue due to the wall being colder is the increased risk of spalling, the outer surface of the external wall becomes colder and ice could form in the brick work more readily. The freeze and thaw cycle can cause damage to the brick surface, known as spalling (Kalnæs & Jelle 2014; Wright et al. 2012; ASHRAE 2013).

2.2.4 Types of internal wall insulation

There are two main application methods of internal wall insulation currently used: it can be installed by bonding a rigid insulation board directly to the wall (dot and dab method) or through building a stud wall and
putting the insulation material between studs or on the front face. Both systems have benefits and drawbacks: the stud wall is thicker, so removes more floor space, but heavier items can be attached to this wall securely afterwards; rigid insulation boards are thinner, so reduces floor space less, however fixings for heavy items would have to go through the board to the original wall behind. Rigid insulation boards can be applied directly onto flat walls, however if walls are uneven a stud wall must be used. Within the stud wall system, either insulation is put between the batons and then covered with a layer of plasterboard, or the insulation panels are put on top of a thin stud wall.

Insulation is available in different forms dependent on its method of installation. It can come in sheets, rolls, it can be foamed in place, or it can be loose filled. When determining the thickness of insulation to be used there is a law of diminishing returns of investment for energy saving, therefore cost and energy saving must be balanced (Al-Homoud 2005; Zagorskas et al. 2014). Most traditional materials are either fibrous or cellular and fit into the categories of organic or inorganic (Al-Homoud 2005). Insulation materials can also be defined by their stage of development and place in the market, these are traditional, modern and future. Traditional materials which are widely used and include mineral wool, expanded polystyrene and polyurethane (Jelle 2011). Modern insulation materials are those which are emerging into the market from development and offer benefits such as being very thin e.g. vacuum insulation panels, gas filled panels and aerogels (Zagorskas et al. 2014). The third category is future materials and these are generally theoretical and use nanotechnology e.g. vacuum insulation panels with closed cells, nano-insulation and dynamic insulation (Jelle et al. 2010; Jelle 2011).

Many widely used insulating materials are plastic which may not be compatible with the functioning of traditional buildings. Traditional buildings are hygroscopic, whereby water in vapour and liquid form is absorbed into its fabric and passes through it to the inside or outside to balance indoor air humidity (Moradias et al. 2012). When a hygrophilic material is used on the internal face of a building, e.g. a polyurethane board, moisture internally can no longer escape through the walls. This can increase indoor humidity and create problems such as condensation, mould growth and associated respiratory health issues. However a study on internally insulating 6 tenement flats with both plastic and natural materials showed no significant increase in moisture within the walls over an 18 month period (Jenkins 2012).

The use of natural insulation materials on heritage buildings allows them to continue to ‘breathe’ (Zagorskas et al. 2014). Petrochemicals are a limited resource and require significant amounts of energy in their processing to produce plastic insulation (Woolley 2006); when considering the whole life cycle of an insulation material, the energy used to produce it and the possibilities for end of life of natural materials may be preferable to currently more widely used options (Wright et al. 2012). Natural insulation has higher moisture absorbency than synthetic materials, allowing them to regulate moisture (Woolley 2006; Wright et al. 2012; Korjenic et al. 2011; Oxley Conservation 2012a). Natural insulations also have slightly higher thermal mass than polymer based solutions, which could offer some buffering effect of high temperatures (Woolley 2006). However, the
choice of natural insulation materials do need to be considered carefully as they are prone to biological attack (Korjenic et al. 2011), and due to their flammability they require fire resistant coatings (Woolley 2006).

2.3 Thermal performance of houses with solid wall insulation

As discussed in Section 2.1.2, solid walls are assumed in RdSAP to have U-values of 2.1 W/m²K, but measurement studies have shown them to have a lower U-value with more variation across buildings. RdSAP also gives assumed U-values for external walls that have been insulated with IWI (DECC 2013). A wall with 50mm of IWI is assumed to have a U-value of 0.6 W/m²K, while a wall with 100mm of IWI is assumed to have a U-value of 0.35 W/m²K (DECC 2013). The Building Regulations 2010 and their associated Approved Document L1B (HM Government; DCLG 2016b) state that if a wall is renovated it must achieve a U-value of 0.3 W/m²K, if this is technically, functionally and economically feasible. Studies based on calculations have shown there are limits to the effectiveness of IWI due to the thermal bridging of elements such as lintels, windows, doors, party and partition walls (May & Rye 2012). One study has shown that there is minimal benefit to be gained by insulating with a greater thickness than 100mm due to bridging (Schnieders 2005).

There have been few measurement studies on the U-values of solid brick walls with IWI installed. However, there are several studies of U-values of walls insulated with moisture permeable materials on historic buildings and those made of stone (Wright et al. 2012; Currie et al. 2013). One completed by Historic Scotland (Currie et al. 2013) measured the effect of interventions on traditional Scottish homes. Only one of those homes measured was constructed of brick, the rest were all bonded stone construction. Further to this, the house with brick walls was not made of English house bricks; from the picture in the report it appears to be constructed of larger blocks. In the Historic Scotland study, these walls were retrofitted with 10mm thick aerogel blankets, this achieved a reduction in U-value from 1.4 to 0.3 W/m²K.

English Heritage commissioned a study that measured 4 solid wall buildings that were dry lined with insulation, the U-values ranged between 0.52-0.75 W/m²K (Rhee-Duverne & Baker 2013), the thickness was unknown but can be assumed by the U-values to be quite low. A study by Stevens and Bradford (2013) measured the pre and post IWI U-values in two English brick houses and a reduction in the U-value of up to 89% was achieved. In contrast between 34% and 61% U-value reduction was achieved in a study by Walker and Pavia (2015) where they measured the U-value reduction potential of seven different insulation materials in a 770mm thick solid brick wall building in Northern Ireland. The reduction in U-value was less because the walls started with a U-value of 1.32 W/m²K, whereas the walls in Stevens and Bradford (2013) work were around 1.5 W/m²K before retrofit. The best improvement in the Walker and Pavia (2015) study was from aerogel boards, with the second best from PIR insulation. In the Retrofit for the Future study, one house had solid wall insulation installed and had U-value measurements done, detailed by Gupta and Gregg (2016). The house was a Victorian solid wall property fitted with IWI on its front facade and EWI on its side and back. The measured U-values were 0.16 W/m²K on the EWI wall and 0.11 W/m²K on the IWI wall; the pre-retrofit U-values are unknown to compare them to so the reduction in U-value is unknown. Also, details on the number of U-value measurements taken
are not provided, so one or two spot U-values could give erroneous results. From the results given it appears that IWI outperformed the EWI.

There have also been few studies on the whole house performance or energy demand reduction due to IWI. In one study where phenolic backed plasterboard was used for IWI, an improvement in air permeability of 57% was demonstrated in one house (Stevens & Bradford 2013), however in another house there was a slight increase in air permeability. In the same study, energy demand reduction due to IWI was measured and there was a decrease in one house of 35% and in another 37% (Stevens & Bradford 2013). The Retrofit for the Future programme (Technology Strategy Board 2013) insulated 12 properties with IWI, 15 with both EWI and IWI and 9 with both cavity and EWI or IWI. Several of the properties post-retrofit energy demands were measured; however there is no pre-retrofit data for comparison. The analysis of the energy demand data by Gupta and Gregg (2016) shows that the four houses with IWI that had gas and electricity data collected had a range of annual gas demands roughly between 8500-15000 kWh. This range is perhaps to be expected because the houses were occupied and people use their homes differently. Harrestrup et al. (2015) detailed the energy efficiency retrofit of a block of 30 flats in Copenhagen. Most of the walls were retrofitted with internal wall insulation, with one wall (constituting less than 1/5 of wall area) fitted with external wall insulation. The building had district heating and the pre-post measured space heating and domestic hot water was presented for the entire block. The annual measured energy demand for the building before retrofit was 156 kWh/m²; this was reduced to 83 kWh/m²; a reduction of almost half. An 1850’s built house was refurbished by Camden Council as part of its Low Energy Victorian House project (Makrodimitri 2010) was retrofitted with IWI; its post retrofit gas consumption was measured to be 68% lower than the predicted pre retrofit baseline.

However it is uncertain how much energy was saved due to IWI in these projects. In the Retrofit for the Future programme (Technology Strategy Board 2013), the apartments studied by Harrestrup et al. (2015) and the house studied by Makrodimitri (2010) all dwellings underwent deep retrofit. The Danish apartments had new windows and MVHR installed; the Retrofit for the future programme houses had various technologies applied to them, such as solar thermal and MVHR; the Low Energy Victorian House had floor and roof insulation installed, gaps filled to improve airtightness, windows replaced, a new heating system with controls, solar hot water and photovoltaics installed. The impact of IWI on thermal energy demand in any project cannot be known due to the other technologies employed.

The National Energy Efficiency Data-Framework (NEED) analyses the gas consumption of homes that have had energy efficiency measures installed under the ECO and Green Deal schemes. The median saving in gas consumption due to the installation of solid wall insulation (EWI or IWI) in 2013 was 15.5% or 2000 kWh (DECC 2016a), in 2014 the median saving was 14.1% or 1700 kWh (BEIS 2017d). However is should be noted that the ECO program targets households that are fuel poor and therefore there could be a significant take-back effect, whereby residents heat their homes to a higher temperature (Hong et al. 2009).
2.4 Measuring homes

2.4.1 Energy efficiency and thermal performance measurement studies

Many measurement studies have measured the energy efficiency and thermal performance of buildings. This review focusses on studies of homes, rather than non-domestic buildings, due to their relatively simple building services and construction methods. Studies on new homes and homes retrofitted to make them more energy efficient have both been reviewed below, first studies of many homes are reviewed followed by more detailed studies of one or two case study homes or test houses.

Two projects that studied the energy efficiency of newly built housing were the Elm Tree Mews Project (Bell et al. 2010) and the Building Performance Evaluation Programme (Palmer et al. 2016). The energy efficiency of the Elm Tree Mews housing project in York was assessed through observing the final stages of construction, measuring the thermal performance of the houses, and then measuring the energy demand of the houses once occupied (Bell et al. 2010). The intent was to separate the way that occupants affect energy demand from the thermal performance of the buildings. To understand the thermal performance of the buildings co-heating tests, U-value measurements and airtightness tests were all used. This study highlights the usefulness of measuring thermal performance as a means to predict energy demand. The predicted energy demand was then compared to measured energy demand; the difference was the impact of occupant behaviour. The detailed measurements taken in this project and comparisons to SAP as a design tool allowed the authors to identify where mistakes were made in the use of the calculation tool and in the construction of the homes. However, it should be noted that while all houses had their airtightness measured and most were monitored, only one house had a co-heating test done and its wall U-values measured. This is a limitation of this project and was likely due to the time, difficulty and expense of these methods.

In another assessment of new homes, Palmer et al. (2016) took measurements from 76 homes as part of the Building Performance Evaluation programme. Before occupation, a subset of 13 homes underwent co-heating tests; once occupied, the study measured heating energy demand, electricity use and indoor temperatures. SAP models were built of these homes, allowing a comparison between SAP calculated and measured heat transfer coefficients (HTCs) and energy demands. The comparison of measured and predicted HTCs was valuable because it identified the gap between design intent (SAP) and what was achieved (measured). Exploratory work was done using airtightness testing and thermal imaging to understand defects in construction, alongside knowledge of the process and recorded issues of construction of each of the houses. This allowed the authors to make a series of recommendations that would lead to the design intent being met.

There have also been many projects measuring the energy demand of homes after they have undergone energy efficiency retrofits (Makrodimitri 2010; Harrestrup & Svendsen 2015; Byrne et al. 2016; Thomsen et al. 2016; Zhao et al. 2009; Technology Strategy Board 2013; Hong et al. 2009). Two large scale projects with interesting insights include the Retrofit for the Future project (Technology Strategy Board 2013) and the Warm Front scheme (Hong et al. 2006).
The Retrofit for the Future project provided funding for the retrofit of 86 social houses and measurements to be done in these homes (Technology Strategy Board 2013). Air tightness tests, infra-red camera surveys and physical inspections were used to understand the buildings’ performance both before and after retrofit. Indoor environmental conditions and energy demand were only measured after retrofit. A full set of measurements was not done in all homes, likely due to the difficulty of collecting data from occupied homes, leading to post-retrofit gas and electricity data being collected or only 23 homes (Gupta, Gregg, Passmore, et al. 2015). Due to collecting no pre-retrofit energy demand data in the homes, the analysis of CO₂ emission reduction was done using modelled pre retrofit values and measured post-retrofit values (Gupta, Gregg, Passmore, et al. 2015). Part of the performance gap is caused by modelling, discussed in section 2.4.3, therefore it may be inappropriate to compare modelled vs. measured CO₂ emissions when calculating a retrofit saving. This limitation of the Retrofit for the Future project means the exact reduction of energy demand or CO₂ emissions cannot be known.

Indoor temperatures, humidity, outdoor temperatures and energy demand data were measured as part of the Warm Front scheme. The scheme installed cavity wall insulation, loft insulation, draught proofing and heating measures in fuel poor households (Hong et al. 2006). Indoor temperature data was collected half hourly in the homes, before, after or both before and after retrofit. The limitations of this study were that space heating energy consumption is calculated from total energy consumption, which may have created some inaccuracy due to not knowing hot water use. Further inaccuracy may have been introduced by using models of thermal performance to normalise the energy consumption. However, the large number of households’ data analysed (1372) made the study very robust and allowed the authors to draw conclusions that energy efficiency retrofit of fuel poor households did not reduce energy consumption as much as expected. Some reasons behind this were revealed through the analysis of thermal images, revealing poor installation of cavity wall insulation. However detailed conclusions around the reasons for poor performance in individual houses were not considered.

Some smaller studies into energy demand in retrofit offer detailed insights into their methods. One of these is a study by Beizaee et al. (2015), where researchers used a highly instrumented pair of semi-detached test houses with synthetic occupancy to measure the effect of zonal heating on energy demand. This controlled small scale test allowed researchers to draw conclusions on the energy saved with small uncertainties.

In another study, 65 Danish apartments were retrofitted and had the energy demand to the district heating system measured pre and post retrofit (Thomsen et al. 2016). Of these, a subset of 3 homes had their indoor environment measured post retrofit. A post occupancy survey was done with the occupants of the buildings; this led the researchers to draw conclusions on the success of the retrofit from both a socio and technical perspective. The windows, walls, door and roof were all upgraded, therefore the individual impact of each measure could not be explored. Further to this without pre-retrofit temperatures there was no comparison to be made pre and post retrofit of indoor environment.
Several houses that used the Better Energy Homes scheme in Ireland took part in a study by Byrne et al. (2016). Houses were instrumented with heat flux plates for the walls, temperature and humidity sensors in the main bedroom and living room, temperature sensor on the flue pipe, an electricity meter and temperature sensors on the flow and return pipes of the radiators. A survey was done on each house to understand its component parts and interview were done with the homes’ occupants. One house was used as semi-controlled test house, with a set heating schedule and occupants agreeing not to enter the rooms being monitored; this high level of control meant it was easier to compare data pre and post retrofit. These detailed measurements allowed quantifiable conclusions to be drawn about the take-back effect being widespread in these homes after retrofit. Harrestrup et al. (2015) measured pre and post retrofit energy demand and post retrofit indoor temperatures of an apartment block that underwent energy efficiency retrofit. Neither the energy demand in each apartment nor the effect of individual energy efficiency measures was disaggregated. The study showed the impact of the take-back effect on energy demand after retrofit through coupling measurements to a model, however detail of the measured thermal performance of the building or individual dwelling effects are unknown. Makrodimitri (2010) compared a semi-detached Victorian house that had a deep whole house retrofit done to two other flats in the same road that had remained in their original state. A large difference in heating demand was found between the two homes that had not been refurbished and differences in energy demand were shown between the retrofitted and original houses. Due to differing internal temperatures and poorly fitting regression models the dwellings energy demands could not be compared accurately. Further to this, the use of occupied homes and homes of different sizes meant any comparison would have been of little value.

The projects above measured a few different factors in many homes. There have also been many smaller projects that measured a small number of houses’ thermal performance in detail. Some studies have focussed on U-value measurements (Li et al. 2014; Baker 2011; Hulme & Doran 2014; Stevens & Bradford 2013; Walker & Pavia 2015; Gupta & Gregg 2016; Rhee-Duverne & Baker 2013; Rye & Scott 2012). Others have done whole house heat loss tests (Sivirou 1981; Stafford et al. 2012; Guerra-Santín et al. 2013; Jack et al. 2017; White 2014). Methodological learning from a few of these projects is detailed below.

One study critically evaluated the U-value measurement of in-situ elements through the use of 15 heat flux plates and temperature sensors on one floor (Pelsmakers et al. 2017). This high-resolution of measurements showed that there was a high variation of U-values across the floors. The author drew the conclusion that measurements across several parts of the floor are needed to understand the varied heat loss and that one or two measurements would produce a highly biased result. Much of this is due to perimeter effects and the presence of joists, so this is unlikely to be as important for walls, but it still relevant. A U-value study done on behalf of Historic Scotland took measurements in-situ of 57 walls, 9 roofs and 1 floor (Baker 2011). It was commented that it was often not possible to know the exact make-up of the elements as they were in occupied homes, and this exploration would be destructive. This lack of knowledge made it difficult to compare the measurements to models, some assumptions needed to be made.
A co-heating test is the main method for measuring whole house heat transfer coefficients. There are few co-heating test studies in real houses, instead they are often done in test houses (Jack et al. 2017; Beizaee 2016; Butler & Dengel 2013). Measuring the HTC is necessary to measure effect of all underperforming elements, individually they are too difficult to measure e.g. thermal bridges (Jack et al. 2017). In one study of energy efficient houses, there was believed to be inaccuracy in the measured HTCs due to the large influence of solar gains on the test results (Guerra-Santin et al. 2013). In a study to investigate the use of the co-heating test 7 teams did co-heating tests in the same house (Butler & Dengel 2013); more accurate results were gained when data was collected for more days and under a range of outdoor temperatures and solar radiations. Through further analysis of this study the reliability of HTC’s has been demonstrated, showing that they can be highly repeatable (Jack et al. 2017).

2.4.2 Overheating measurement studies

There have been several studies investigating overheating in UK homes (Wright et al. 2005; Firth & Wright 2008; Hulme et al. 2013; Beizaee et al. 2013; Lomas & Kane 2013; Baborska-Narozyń et al. 2017; Morgan et al. 2017; Tabatabaei Sameni et al. 2015; Vellei et al. 2016; Toledo et al. 2016; Pana 2013). A few of these have measured many houses in the housing stock. A large study by Lomas and Kane (2013) measured living room and bedroom temperatures of 268 of the city of Leicester’s homes in 2009. The sample measured was statistically representative of the socio-technical characteristics of Leicester’s stock. In another wider stock survey including the whole of England, indoor temperatures were measured in 207 homes by Beizaee et al. (2013). 122 homes in London were part of an overheating study by Pathan et al. (2017), indoor temperature measurements were collected with in-depth questionnaires investigating factors including socioeconomic status, ventilation patterns and appliances use. This study was representative technically of the London housing stock by selecting different dwelling archetypes, amount of thermal mass and ages; however the sample of occupants were self-selected volunteers chosen through a convenience sample. This study recommended using weather stations located close to the households due to varying microclimates.

These stock studies drew statistically significant conclusions on which housing characteristics were most likely to have higher temperatures; vital for understanding overheating across the housing stock. However Beizaee et al and Lomas and Kane (2013; 2013) both commented on errors in the data arising from inexpert placement of temperature sensors, this resulted in researchers making judgements on when to remove some data. Some comments were also made about household retention, Pathan et al. (2017) needing to recruit new households once the study had started due to householders leaving.

Smaller studies do not suffer as much from these issues; they can be managed and run by a small team of people who can place the temperature sensors themselves. In one such study of new build flats built to Passivhaus standards, indoor temperatures were measured and occupants were surveyed about their occupancy patterns (Tabatabaei Sameni et al. 2015). The insight into occupancy patterns allowed the author to calculate the amount of overheating that occurred in occupied hours; a useful insight when considering the
health and wellbeing of occupants in social housing. However, the authors commented the short monitoring periods made it difficult to compare the measured data to annual thresholds of overheating.

In another study, indoor temperatures were measured in 3 rooms of 26 new build dwellings (Morgan et al. 2017). Data was also collected on the thermal performance of the homes, the ventilation, appliance use and non-structured interviews done with the occupants to understand occupancy. The detail in this investigation allowed the conclusions to be drawn that design and occupancy factors had a larger influence on overheating compared to climatic factors.

Studies of just a few houses are sometimes used to do in-depth investigations into overheating. In one study by Jones et al. (2016) authors compared very similar new build homes in England, one built to current building regulations and two others built to the higher Code for Sustainable Homes level 5 standard. This method was able to show the notable difference in temperature caused by thermal efficiency. In another small study Pana (2013) compared indoor temperatures and occupant feedback to quantify overheating in four bedrooms in two houses of differing orientations. This allowed the author to draw the conclusion that orientation has little effect on bedroom temperature during occupied hours. In both of these small case-studies the use of occupied houses introduces significant uncertainty to the results, any variation or similarity seen may have been due to occupant effects. One study measured indoor temperatures in a house that underwent deep retrofit of a Victorian house that included IWI, loft and floor insulation, new windows and draft proofing (Makrodimitri 2010). Indoor temperatures in summer were generally within the comfort range of 21-25 °C, used to assess overheating. However, on one floor of the house with increased solar gains the indoor temperature regularly exceeded 25 °C. This study from 2010 uses static criteria to assess overheating, overheating criteria have now progressed to adaptive criteria (section 2.5.1). The author has also compared of indoor temperatures in summer between the refurbished house and a nearby flat in its original state; it may be inappropriate here to compare the two considering different propensities for overheating of different build types (section 2.5.2).

2.4.3 The performance gap

The performance gap is the difference between the predicted and measured performance of a building (Gupta & Gregg 2016). It is believed to be both significant and wide-spread (ZCH 2014); to understand and close the performance gap it is necessary to accurately measure how well buildings perform (Butler & Dengel 2013). The performance gap arises from three primary sources: the inaccuracy of models (Rhee-Duverne & Baker 2013); poor build or retrofit (ZCH 2014; Bell et al. 2010); or unexpected occupant behaviour (Guerra-Santin & Itard 2010; Audenaert et al. 2011). The inaccuracy of model predictions or poor build quality can lead to a performance gap in airtightness, in U-values, or in whole house heat loss; examples of each of these are provided below. This underperformance of the fabric and the introduction of imperfect or unexpected occupant behaviour can lead to a performance gap in energy demand and CO₂ emissions. Examples of these are given firstly of new build projects then retrofit projects; this review is centred on domestic buildings only.
Several studies have found performance gaps found between the design and measured airtightness. When studying the Elm Tree Mews low carbon housing trial the airtightness of the new build dwellings were on average 7 m³/(h.m²) at 50Pa, this was significantly higher than the target of 3 m³/(h.m²) at 50Pa (Bell et al. 2010). In another new build study a third of homes did not achieve the designed airtightness (Palmer et al. 2016). In a study detailing the deep retrofit of two homes, one built in the 1990s and the pre-1919, the intended airtightness for neither was met (Gupta & Gregg 2016). In the whole house retrofit of the Victorian house the author implies that the airtightness target was met; it was reduced from 30 m³/h/m² to 6.5 m³/h/m², through special attention to airtightness including filling gaps and cracks and installing double glazed windows (Makrodimitri 2010).

Examples of a performance gap have also been found when measuring U-values. One measurement study of U-values, primarily traditional Scottish stonewalls, identified that U-value calculation software overestimated the U-values of traditional solid walls (Baker 2011). A performance gap is found when comparing many measurement studies of solid walls to those provided in RdSAP or to U-value calculation software, as detailed in Table 2-2. In the deep retrofit project mentioned above, the U-values of the walls were measured post retrofit (Gupta & Gregg 2016). In the older house the target U-value was exceeded on one wall, but not achieved on the other; in the newer house the target U-value was exceeded by almost double. In a new build house timber framed house wall U-values were 65% higher than designed due to optimistic thermal bridging factors used in a model (Bell et al. 2010); however once as-built thermal bridging factors were used, the model could be used to accurately calculate the U-values. There have been studies of other building elements including floors; a significant performance gap of between 12-28% was found when comparing measured floor U-values to modelled values (Pelsmakers et al. 2017).

There are few homes that have had their heat transfer coefficients (HTCs) measured and compared to models; this is likely due to the difficulty and expense of the co-heating test: the main method used to measure HTCs. The Elm Tree Mews housing project in York used a co-heating test to compare the design versus as-built heat transfer coefficient (HTC) of a newly built timber framed house (Bell et al. 2010). The fabric HTC was 54% higher than it was designed to be, 169 W/K instead of 100 W/K; this was due to overestimating fabric performance at design stage. SAP was used to predict the fabric HTC, which it did very accurately once the correct U-values and thermal bridging values were used in the model. In another new build study, in which thirteen houses were measured, nine had a worse HTC than the design stage SAP predicted (Palmer et al. 2016); however the remaining four were better than predicted. In a study of two low-energy houses, co-heating was used to measure the HTCs and there was a notable gap between the Passivhaus Planning Package (PHPP) predicted values and those measured (Guerra-Santin et al. 2013). However, in this study the authors believed the gap to be caused by the measurement method rather than the model or the build quality; this is a less sited but possible source of performance gap. Thirty of the thirty-four co-heating tests reported by Stafford et al. (2012), show a performance gap between the predicted and measured heat loss. The performance gap was as large as 120%, however four of the houses performed better than predicted. In one of
the Low Energy Victorian House project houses, a whole house retrofit was done including fabric and building services measures (Makrodimitri 2010). The results of a co-heating test post retrofit showed that the house achieved the target heat loss and that there was no performance gap.

When the target thermal performance is not attained, there will likely be a performance gap in the between the calculated and measured energy demand and CO\textsubscript{2} emissions. There have been several studies of this performance gap in new homes. In a measurement study of new homes in the Elm Tree Mews low carbon housing trial, it was identified that the houses’ thermal performance and system performance were worse than intended (Bell et al. 2010). This led to the whole development emitting an extra 3.7 tonnes CO\textsubscript{2}/annum (Bell et al. 2010), this was more than double the expected amount. In another study of 76 homes, a subset of Innovate UK’s Building Performance Evaluation Programme, CO\textsubscript{2} emissions were measured to be 2-3 times higher than intended (Palmer et al. 2016); there was almost no relationship between CO\textsubscript{2} emissions modelled in SAP and those measured in the occupied homes. There was fabric underperformance and difficulties both installing new technologies and in occupant use of technologies; these all contributed to the performance gap (Palmer et al. 2016). An evidence review of the gap concluded that it exists due to the difference in design and the ability to build it, poorly integrated services and unintended bridging, incorrect calculation assumptions and site teams that lack expertise in energy efficiency (ZCH 2014).

There have also been several studies comparing measurements of existing homes, which were built to the building standards of the time, to RdSAP models of the houses. In one study energy consumption and indoor environmental data was measured in ninety-three solid wall buildings (Birchall et al. 2011). The energy consumption measured was generally less than RdSAP estimates. 36% of the homes in the study were under-heated; this is an example of unexpected householder behaviour not matching idealised model parameters. In a study measuring a Victorian and a modern house energy use was lower in than modelled using SAP (Gupta & Gregg 2016). A study on German homes showed that occupants’ energy demand for heating was 30% less than predicted by the German national calculation methodology (Sunikka-Blank & Galvin 2012). Older homes do not appear to have the same performance gap as new homes, instead it appears that models often over-predict the amount of energy used in homes.

This over-prediction means that the energy savings predicted by models cannot be realised once homes are retrofitted because they started from a better energy efficiency than models predict. One study defined this as the pre-bound effect (Sunikka-Blank & Galvin 2012) and has been seen in UK, French, German and Dutch studies. In the Retrofit for the Future project only 3 out of 45 house retrofits met CO\textsubscript{2} emission reduction targets (Gupta, Gregg, Passmore, et al. 2015). In a study analysing the effect of the Warm Front scheme in 1372 households there was a difference performance gap found between measured and predicted energy savings (Hong et al. 2006). In a project retrofitting a Victorian house a 75% CO\textsubscript{2} reduction was achieved, this missed the 80% reduction target (Gupta & Gregg 2016), making it 28% greater than predicted.
In the study of a block of flats retrofitted with internal wall insulation, MVHR and new windows in Copenhagen measurements were compared to building energy simulations (Harrestrup & Svendsen 2015). Before retrofit a model was produced which predicted the energy demand of the building within 2.6% of that measured; after retrofit the model predicted over 10% higher energy savings than were achieved. This led the researchers to investigate and find a performance gap between the design and actual performance of the MVHR system and the air tightness of the building; higher indoor temperatures than expected (the take-back effect); and people opening windows more than expected. Arguably the model, the occupant behaviour and the as-built system performance gap issues were all seen in this project. In a study of 10 blocks of flats retrofitted in Geneva, only 42% of the predicted energy consumption reduction was achieved (Khoury et al. 2016). The performance gap here was identified to be due to the inputs to the models and to underperforming fabric post-retrofit. Analysis of homes retrofitted under the Irish Home Energy Saving Scheme showed that while homes performed thermally, carbon reduction was not achieved in homes after the retrofit of wall insulation (Byrne et al. 2016). The whole house deep retrofit of a large Victorian house resulted in a measured gas demand of 24000 kWh, much higher than expected (Makrodimitri 2010); this was despite the measured HTC meeting the targeted HTC. In both the studies by Byrne et al. (2016) and Makrodimitri (2010) this was believed to be due to high indoor temperatures, the comfort take-back effect, this is an example of a performance gap caused by occupants not behaving as expected. However, in a study of Danish apartments it was found that Be10, Denmark’s national calculation tool which is a monthly heat balance method, predicted energy demand both pre and post retrofit very accurately (Thomsen et al. 2016). This perhaps shows that the UK’s National Calculation Method: SAP could be improved.

Before retrofitting a home, the performance gap could be reduced by measuring the actual performance of a home, rather than depending on prediction models. The performance gap between assumed and measured solid wall U-values has implications for the cost-effectiveness of retrofit (Chambers et al. 2015; Rhee-Duverne & Baker 2013). If the original performance of a house is underestimated, the effectiveness of a retrofit scheme may be worse than expected (Hulme & Doran 2014; Rhee-Duverne & Baker 2013). This was demonstrated in a study by Sunikka-Blank & Galvin (2012) where dwelling ratings overestimated the energy savings that were possible from retrofit and the payback time was underestimated. This is corroborated by several other authors stating that using standard assumptions when modelling and retrofitting solid wall houses could have serious implications on the payback after retrofit (Stevens & Bradford 2013; May & Rye 2012; Oxley Conservation 2012a). Evaluating the economics of solid wall insulation is not appropriate using current assumed U-values (Gupta, Gregg, Passmore, et al. 2015). This is clearly a known phenomenon; UK Government schemes took account of performance gap effects in the Green Deal and ECO by using ‘In-Use factors’ (DECC 2014b); these modified the expected savings by a percentage to account for poor installation, models not matching reality and take-back effects. To achieve predicted CO₂ emissions reductions from building retrofit, building models must be able to estimate energy demand accurately (Kavlic et al. 2010). If original U-values are better than expected, fabric improvements could be over designed, which could increase the risk of unintended consequences for the condition of buildings and occupants (Rhee-Duverne & Baker 2013).
It has been found in many studies that people change their energy demand habits after renovation of a house (Makrodimitri 2010; Hong et al. 2006), often by increasing the indoor temperature. Reducing this effect is impractical as it removes occupants’ right to use the amount of energy they would like to, increasing temperature also has desirable health benefits. Two ways to reduce the performance gap are to make models such as SAP match reality more closely and to improve the quality of retrofit. There are several examples of improving simple models, such as SAP, by introducing measured components, i.e. using the core calculation method, but by replacing assumed U-values or heat transfer coefficients with measured values. Birchall et al. (2011) and Stevens and Bradford (2013) did this when assessing the thermal performance of solid wall buildings; they found that the heating energy consumption was then in-line with the improved SAP model prediction. Chambers et al. (2015) produced ‘improved SAP’ models by using measured airtightness and U-values, the model was then compared to standard SAP models. It was found that the standard SAP model predicted a higher demand than the improved SAP model by 7.5 – 22%. More generally it has been commented by several authors that a way to reduce the performance gap when retrofitting solid wall buildings is to update the RdSAP U-value tables. As discussed in 2.1.2, several measurement studies have found solid walls to have a lower U-value than assumed; in a stock model using U-values of 1.3 W/m²K not 2.1 W/m²K energy demand was reduced by 16% (Li et al. 2014).

2.5 Overheating in dwellings

In the 2015-2016 English Housing Survey (EHS) 7% of occupants reported that their homes currently overheat (DCLG 2017b). One study by Beizaee et al. (2013) monitored 207 homes across England in the cool summer of 2007 and showed that many rooms would be considered uncomfortably cool in summer. However, due to the diversity in the building stock there were some homes that did overheat; within the same study 21% of bedrooms were assessed as overheating (Beizaee et al. 2013). A study by Lomas and Kane (2013) monitored indoor temperatures of a socio-technical representative sample of Leicester’s homes in 2009 assess overheating. They found that only one living room and 5 bedrooms in a sample of 230 free-running dwellings overheated according to adaptive criteria; like in the study by Beizaee et al. (2013) rooms would be considered too cool. However, using a fixed threshold of 26 °C, 15% of bedrooms overheated for more than 30% of the summer (Lomas & Kane 2013). Temperatures were measured in 122 homes in London in 2009 by Pathan et al. (2017), using adaptive criteria they showed that many home are currently overheating: 29% of living rooms and 31% of bedrooms. These measurement studies indicate that there is a current issue of overheating in many bedrooms across the UK, and an issue with many whole dwellings in London. Overheating is occurring in homes across the UK from the South-East of England to Scotland, leading to increased concern in this temperate climate (Lomas & Porritt 2017). However, there appears to be a mismatch between the number of people reporting overheating in the English housing survey, and the prevalence of overheating in measurement studies. This could indicate that the overheating assessment criteria do not accurately assess when occupants will feel too hot.
The temperature of Central England has increased by 1ºC since the 1970’s (Jenkins et al. 2010). The UK Climate Projections 2009 predict that mean outdoor summer temperatures will increase by 4.2 ºC in southern areas of the UK under a medium emissions scenario at the 50% probability level (Jenkins et al. 2010). It is widely accepted that overheating in homes will become a bigger issue in the future due to this warming climate (Morgan et al. 2017; Taylor et al. 2014; Gupta & Gregg 2012). Modelling studies have shown that Victorian terraces, which are currently the coolest part of the building stock, may overheat in bedrooms from the 2020’s (Ji et al. 2014) These issues may be prevented through passive overheating mitigation, or occupants would need to be provided comfort through fans and air conditioning (Gupta, Gregg & Williams 2015).

2.5.1 Defining overheating

Overheating is generally judged as the upper limit for thermal comfort (Dengel & Swainson 2012), and is closely linked to thermal comfort as it is people’s perception of a building being too hot. There are varying definitions of overheating (DCLG 2012), a widely accepted definition is when indoor temperature exceeds a benchmark temperature for a set period of time. This temperature may be related to health, comfort, or productivity in the case of work places (CIBSE 2006). There are no maximum temperatures not to be exceeded described in the Building Regulations for homes or other buildings, therefore recommended limits are provided by British Standards (2007b), CIBSE (2015b; 2013; 2017) and ASHRAE (2013).

The temperature ranges used for assessing summer comfort and therefore overheating tend to be operative temperatures, not air temperatures: these are believed to have a better relationship to the way people feel in a space because they incorporate both air and mean radiant, and air speed effects (BSI 2005, Equation 1). The operative temperature ranges are dependent on the whether it is free-running or mechanically cooled and the purpose of the building i.e. dwelling, shop restaurant etc.. Mechanically cooled buildings tend to have smaller acceptable temperature ranges and are based on Fanger’s (1970) model of thermal comfort. CIBSE Guide A recommends that the operative temperature in mechanically cooled dwellings in summer in living rooms and bedrooms should be between 23-25 ºC. In free-running dwellings it is assumed that people adapt their behaviour and clothing due to outdoor conditions, this is the adaptive theory of comfort, therefore the indoor comfort range has a relationship with outdoor temperature (CIBSE 2015b; CIBSE 2013; CIBSE 2017; BSI 2007b); this relationship is between the indoor range of operative temperatures for comfort and the exponentially weighted running mean outdoor temperature of the previous day. Adaptive comfort is assumed to be applicable where occupants have access to operable windows, and these windows can be opened to a minimum of 1/20 of the floor area of the room (CIBSE 2017).

\[
T_o = \frac{T_a\sqrt{10v} + T_{mr}}{1 + \sqrt{10v}} \quad \text{(Equation 1)}
\]

Where:

- \(T_o\) is the operative temperature, ºC
- \(T_a\) is the air temperature, ºC

39
\( v \) is the air velocity

\( T_{\text{mr}} \) is the mean radiant temperature, °C

There are several widely used methods for assessing overheating suitable for homes (ZCH 2015a), these include the SAP Methodology (DECC 2013), CIBSE Guide A (2006), CIBSE Guide A (2015a), CIBSE TM52 (2013), CIBSE TM59 (2017). The SAP Methodology (DECC 2013), CIBSE Guide A (2006), CIBSE Guide A (2015a) all use static criteria for assessing overheating, these are therefore not suitable for assessing overheating in homes where adaptive opportunity is possible. To address this CIBSE produced TMS2 and TM59 (2013; 2017), these both use adaptive criteria taken from BS EN 15251: 2007 (2007b). CIBSE TM52 is used to assess both modelled and measured data and is suitable for all buildings. CIBSE TM59 is focussed on assessing homes and describes both input criteria for a dynamic thermal model and assessment of the data produced from the model.

2.5.2 Causes of overheating

Overheating can be caused by one factor, or it can be the compound effect of many smaller factors (Richard Partington Architects 2012; Taylor et al. 2014). Overheating is caused by heat not escaping readily enough from the inside of a building, therefore causing high indoor temperatures. The gains and the losses in a building must balance appropriately to prevent overheating.

A highly insulated house will not allow for heat to escape as readily as one with no insulation. Recent reports by the Zero Carbon Hub (ZCH 2015c; BRE 2014) and the Building Research Establishment (BRE 2014) have highlighted summertime overheating as a growing problem in modern, well insulated and airtight dwellings. A survey of Environmental Health Officers, housing providers and consultants revealed that they identify overheating occurring in highly insulated dwellings (Taylor 2014). UK homes built to Passivhaus standards, with high insulation and air tightness, were measured and shown to overhear (Tabatabaei Sameni et al. 2015). A study of 26 new build Scottish dwellings, with the associated energy efficiency of a new build home, showed that 54% of them overheated for 6 months of the year or more (Morgan et al. 2017). A comparison of two houses in the south of England, one built to current building regulations and the other to the higher Code for Sustainable Homes level 5 standard, showed that the higher insulation standards and airtightness led to higher indoor temperatures (Jones et al. 2016). This is the unintended consequence of building energy efficiency policy (Shrubsole et al. 2014); a focus on energy efficiency and fuel poverty in winter, but little is done about overheating in summer (Lomas & Porritt 2017).

Homes built to low insulation standards have been shown in measurement studies to be at the lowest risk of overheating (Firth & Wright 2008; Lomas & Kane 2013) The Energy Follow-Up Survey (EFUS), which is based upon the earlier 2010/11 EHS, reports that occupants of pre-1919 dwellings are the least likely to report a problem with overheating (DECC 2014a). The 2015-2016 English Housing Survey (DCLG 2017b) supports this, with fewer occupants of pre-1919 dwellings reporting overheating compared to other age bands. A measurement study by Lomas and Kane (2013) of Leicester’s homes in 2009 found that solid wall houses have the lowest risk of overheating. A study by Beizaee et al. (2013) monitored 207 homes across England in 2007.
and found that pre-1919 dwellings were the least likely to overheat. However, as these buildings’ thermal standards are increased through retrofit there is a risk that pre-1919 solid wall dwellings could overheat (Lomas & Porritt 2017; Dengel & Swainson 2012).

In a measurement study of a house with IWI, indoor temperatures stayed within comfort limits in the summer of 2009 (Makrodimitri 2010). However modelling studies have shown that IWI increases indoor temperatures in solid wall dwellings (Porritt et al. 2012; Gupta & Gregg 2013; Mavrogiani et al. 2012; Ji & Webster 2012). Porritt et al. (2012) used dynamic thermal modelling to quantify the effect of a range of retrofit interventions, including EWI and IWI, on overheating risk during the UK 2003 heat wave period. It was found that IWI could increase overheating degree hours for west facing rooms in solid wall end terrace houses, whilst EWI was found to reduce overheating for all orientations and occupancy profiles. Gupta and Gregg (Gupta & Gregg 2013) found through dynamic thermal modelling that IWI will, in most cases, lead to increased overheating, whilst EWI could in some cases reduce overheating compared to an uninsulated house. Ji and Webster (2012) carried out comparative dynamic thermal modelling of IWI and EWI on a pre-1919 end terrace house using a calibrated model, and found that IWI resulted in significantly greater overheating than EWI. Mavrogiani et al. (2012) modelled the effect of internal wall insulation as a retrofit measure for London dwellings and reported an increase in maximum daytime temperatures of 0.61 °C during a sample of five days of the hottest consecutive weather. Modelling work such as these have led the BRE to discourage the use of internal wall insulation compared to external wall insulation due to its potential overheating risk (BRE 2014). Both the BRE and DCLG have identified that there is uncertainty in modelling work and there are gaps in knowledge with regards to the summer performance of houses with SWI particularly with regards to the its influence on thermal mass (BRE 2014; DCLG 2012).

Homes in the south of the UK have the biggest overheating potential (DCLG 2012), this is to be expected as it has the warmest climate. A further locational factor is whether a house is in an urban heat island. An urban heat island is where many buildings are closely clustered together with a lack of green spaces, this creates a hotter outdoor environment due to absorption and re-radiation of heat (Richard Partington Architects 2012). This hotter outdoor environment leads to warmer indoor temperatures, and therefore an increased overheating risk (Richard Partington Architects 2012; Lomas & Porritt 2017; Taylor et al. 2014).

Built form has a much larger effect on overheating than the urban heat island effect (Mavrogiani et al. 2012). Analysis of 260 homes in Leicester revealed that flats were at the greatest risk of overheating (Lomas & Kane 2013). Another study of the UK showed that purpose built flats and end terraces had the highest likelihood of overheating (Firth & Wright 2008). In a survey of environmental officers and housing providers overheating was identified most often in flats, both new and converted (Taylor 2014). In particular, 21% of the reports of overheating in this study were from pre-1919 converted flats, but there were no reports from pre-1919 houses. This appears to be because when older properties are converted and split into flats the original natural stack ventilation is prevented, also the conversion of roof spaces and leaving them uninsulated causes overheating in top floor flats (Taylor 2014). It has been shown in other studies that top-floor purpose built flats also
overheat, often due to a lack of shading (DCLG 2012). The 2015-2016 English housing survey showed that small terraced houses currently overheat less than many other house types (DCLG 2017b).

To reduce internal temperature in highly insulated buildings sufficient ventilation is required to remove excess internal gains (Taylor 2014). Some dwellings are difficult to ventilate effectively due to their built form, such as single aspect dwellings (Lomas & Porritt 2017; Taylor 2014), which due to a lack of cross-ventilation can be difficult to purge of air.

Solid wall buildings have significant thermal capacity due to their thick masonry walls. Thermal mass is useful in both winter and summer as it averages fluctuations in indoor and outdoor environment, absorbing and desorbing heat to the indoor environment at times of high and low indoor temperature respectively. When external wall insulation is installed on a solid wall building the internal environment retains the benefit of the thermal mass. However when external walls are insulated internally they are isolated from the thermal mass. There are two opposing scenarios that decide whether internal wall insulation contributes or prevents to overheating in a highly insulated house. The theory of IWI contributing to overheating is that when the temperature of the room increases the mass is not available to remove and store excess heat. (Oxley Conservation 2012a; Arup Research + Development and Bill Dunster Architects 2005; Mavrogianni et al. 2013), therefore the temperature in the room rises sharply. The alternative scenario is that because the mass is isolated it is not available to be heated throughout the day by warm air and sunlight (Richard Partington Architects 2012), therefore the heat is stored mainly in the air and can be easily purged through ventilation of the house (Hacker et al. 2005). This lack of mass may also result in further energy savings as it does not need to be heated in winter. Many believe that external insulation is better for hotter climates and internal for cooler climates, but for seasonal climates such as that of the UK there is a debate.

Solar gains is the largest contributor to gains in summer which lead to overheating (DCLG 2012). Intense solar radiation, even during low external temperature could cause a warm internal environment due to radiation passing through the windows then being absorbed by surfaces within the room, this is the greenhouse effect (Richard Partington Architects 2012). Highly glazed dwellings, particularly those which are south facing, have an increased overheating potential (Taylor 2014). Many houses overheat primarily due to gains through windows, however solid wall terrace buildings primary overheating potential is due to conduction of solar gains through their walls (DCLG 2012).

The National House Building Council (NHBC) state that occupant behaviour can induce overheating (Richard Partington Architects 2012). A study of 26 well insulated building in Scotland showed that occupant behaviour can be a very large contributing factor to overheating (Morgan et al. 2017). Occupant behaviour lead to internal gains within a building due to the activity of people and electronic equipment used. People within the building release heat, proportional to the activity that they are doing, these are metabolic internal gains. When electronic equipment is used it releases heat, such as lights and appliances including televisions, cookers, fridges. Overheating occurs more often when houses are occupied during the day (Taylor 2014), longer occupancy periods release more gains into the indoor environment. A modelling study Porritt et al. (2012)
showed that IWI can increase the risk of overheating in houses occupied by the elderly, due to the longer occupancy period and because they are present for the hottest period of the day. Excess internal gains can also come from centralised central heating (Lomas & Porritt 2017), reducing gains from hot water distribution can reduce risk (Taylor 2014).

There is only a limited feedback loop to house builders concerning overheating, this could increase the prevalence of overheating. House builders record complaints from purchasers of their buildings, however there are generally no procedures in place to record overheating as a defect (Richard Partington Architects 2012). This will likely result in the same design of house being replicated elsewhere with no lessons learnt from the original design. A similar situation could occur in the retrofit industry, where there appear to be no feedback loops to installers or manufacturers. A number of house builders and managers were consulted on their experiences of overheating in their properties by DCLG; of the respondents 5 said they had received formal complaints about overheating (DCLG 2012).

Criterion 3 of the Approved Document L1A recommends the use of SAP to check for overheating in new dwellings. However there is no such recommendations for existing dwellings being improved (DCLG 2016a; DCLG 2016b). A recent study of new build properties by Morgan et al. (2017) showed that SAP is under-predicting overheating: only 2 out of 26 houses in the study were predicted to overheat. Whereas, 19 of 26 houses had a room that overheated for more than 10% of the year, and all overheated at some point. This indicates that SAP may not be an appropriate tool for assessing overheating.

2.5.3 Consequences of overheating

Generally, being too hot cause people discomfort (Fanger 1970). Overheating can also affects people’s health and in extreme cases can cause death, with a strong link found between temperatures higher than usually experienced within a region and excess mortality (Armstrong et al. 2011). Analysis of all deaths in England and Wales between 1998-2007 show that there is a significant relationship between temperature and the number of deaths (Brown et al. 2010). It is estimated by Public Health England (2015) that excess deaths in England occur above 25 °C, with an extra 75 deaths per week per 1°C rise in temperature. There are also some regional differences shown in a study by Armstrong et al. (2011), where threshold temperatures were identified at which mortality begins to rise. In London the maximum daily temperature is 24.7°C, a small increase in temperature results in a significant amount of extra deaths. A heat wave is not necessary to cause extra deaths, a single day above the threshold temperature results in more deaths than a series of days constituting a heat wave (Armstrong et al. 2011). An extra 2000 deaths occurred during the 2003 heat wave in England and Wales; many of these deaths occurred in London as those who live in cities experience higher temperature caused by the urban heat island effect. Each year there are between 1100 -2000 excess heat related deaths (ZCH 2015b). There has already been increased heat-related mortality and decreased cold-related mortality in some regions as a result of a warming climate (medium confidence) (IPCC 2014), this will likely continue as the climate continues to change.
Studies linking temperature with illness and mortality look purely at external temperatures, these cannot be directly linked to indoor temperature (DCLG 2012). There is debate whether it is indoor or outdoor temperatures which cause an increase in mortality and morbidity; for a given outdoor temperature in a city there are a range of indoor temperatures across the different buildings (DCLG 2012). Arguably if people spend up to 95% of their time in artificial indoor climates (Fanger 1970), it is likely that it is the indoor temperatures that effect health. There is a strong relationship between outdoor temperature and deaths, however no proven relationship between indoor temperature and health. Due to the lack of evidence and the variation between individuals it is difficult to set a threshold temperature for maintaining health (ZCH 2015b).

There are increases in most causes of death in hot weather because heat affects people with many different underlying health conditions (DCLG 2012; PHE 2015). Deaths occur both due to direct heat illness, stressing the cardiovascular system and due to indirect illness because an increase in outdoor temperature decreases air quality (PHE 2015). Hospital admissions do not increase as much as mortality, it is assumed people get unwell and die before seeking help from health care services (ZCH 2015b). The elderly are young children especially vulnerable to heat related deaths (Johnson et al. 2005), however all of the population are susceptible to illness in extreme weather (PHE 2015).

Further to the direct impacts on health the Zero Carbon Hub (2015b) also reviewed the wider impact of overheating in homes on mortality, illness and discomfort. The sleep deprivation caused by overheating could result in a lack of productivity at work the following day. Long term sleep deprivation can lead to overall poor health (ZCH 2015b). Both the impacts on health and productivity could impact the economy, with costs to the NHS and to businesses as incidents of lost days of work and workplace accidents occur, however these are currently ill defined (ZCH 2015b).

2.5.4 Preventing overheating

The Building Regulations for England and Wales recommend limiting gains for the conservation of fuel and power (HM Government n.d.). In the Approved Document L1A for new dwellings it is recommended that this be achieved by “an appropriate combination of window size and orientation, solar protection through shading and other solar control measures, ventilation (day and night) and high thermal capacity.” Although these design methods are suitable for new build properties, it is unlikely that the size or orientation of glazing or its thermal capacity would be altered on a retrofitted property. There is a difference between the mitigation strategies available for older dwellings compared to new dwellings.

One method of preventing overheating is to install air conditioning. Levels of air conditioning are currently low. A recent study across London found that only 3 in their sample of 89 dwellings had air conditioning (Mavrogianni et al. 2016). The EHS follow-up study found that only 3% of households have air conditioning (Hulme et al. 2013). Although levels are currently low, if overheating cannot be prevented through passive mitigation methods home owners will install air conditioning (DCLG 2012). This would be counter-productive; the energy demand reduction in winter from energy efficiency measures could be offset by a new cooling load in summer. Ceiling fans are a low-cost and lower energy alternative to preventing overheating, however
passive measures aimed at mitigating high temperatures before they occur should be exhausted first (Gupta, Gregg & Williams 2015). Overheating mitigation needs to be installed now to prevent overheating under a future warmer climate (Morgan et al. 2017)

At a neighbourhood or city scale methods such as urban greening can help to prevent overheating by reducing the urban heat island effect, further to this it increases air quality, reducing the health related impacts of overheating on people (PHE 2015). Here methods on an individual house scale are discussed as a method to mitigate overheating due to the installation of IWI.

To remove heat from the house, ventilation strategies can be used. In a domestic setting thermal mass and enough ventilation to implement a night cooling strategy are believed to be currently sufficient to prevent overheating (DCLG 2012; Richard Partington Architects 2012). It was a recommendation from one monitoring study of UK homes that overheating would be mitigated by extra ventilation (Vellei et al. 2016). In the domestic context this means windows that can be opened wide enough and for an adequate amount of time. The ability to open windows will also affect the occupants experience as increased air velocity passing over the skin will allow comfort to be attained in higher air temperatures (Fanger 1970). However, night purging of air would not cool the mass significantly enough to prevent overheating if external air is not sufficiently cool at night (Hacker et al. 2005), this could occur during heat waves.

Solar gains can be reduced through the use of blinds, curtains, shutters and shading, and high albedo walls (Porritt et al. 2011; Capon & Hacker 2009). A dynamic thermal modelling study by Porritt et al. (2012) analysed overheating risk during the UK 2003 heat wave; it was found that external shutters offer the best mitigation of overheating potential in most house types. In a modelling study of houses in Oxford under future weather by Gupta and Gregg (2012) solar shading was the most effective method of overheating prevention, with high albedo surfaces and increasing available surface mass also effective. A study by Liu et al. (2015) of a house retrofitted with EWl in Sweden found that external blinds were effective at producing comfortable environments in summer. External solar shading can be optimised to the orientation of the window to protect from the summer sun either high or low in the sky and to increase gains in winter and decrease gains in summer (Katunský & Lopušniak 2012). For south facing windows with high sun, awnings are appropriate; for west facing, low sun, louvres are appropriate; shutters can be used for any orientation of window (Richard Partington Architects 2012). These solutions can be opened or withdrawn, so the benefits of solar gains can be received in winter. In South facing rooms in particular, light walls are highly effective at reducing overheating, by reflecting the solar radiation (Porritt et al. 2011).

Combining more than one method of mitigation can be the most effective way of preventing overheating. A measurement study of Passivhaus in Slovenia showed that window opening at night and solar shading can create a comfortable indoor environment (Mlakar & Štrancar 2011). A dynamic thermal simulation study on a well-insulated terraced house in the Netherlands shows that external shading and ventilation significantly reduces summer cooling load and does not significantly increase winter heating load due to reduction in solar gains (van Hooff et al. 2016). A dynamic thermal simulation study of retrofitted dwellings across Europe by
Psomas et al. (2016), report that ventilation and shading were the most useful combined measures to prevent summer overheating. A dynamic thermal simulation study by Mavrogianni et al. (2014) showed that the indoor temperature inside internally insulated solid wall dwellings could be significantly reduced through a combination of night ventilation using windows and blinds closed in the day, however overheating risk could not be fully mitigated. The SNACC project found that when residents were surveyed about overheating mitigation measures they were highly willing to adapt their behaviour by closing window coverings in the day and opening windows at night (Williams, 2012).

Occupants are often unaware of the best practice of shading and ventilation (Baborska-Narożny et al. 2017), which can make mitigation ineffective. External shading was rare in the study of London dwellings by Mavrogianni et al. (2016), with only 5 of 89 households surveyed having external shutters, awnings, overhangs, low-emissivity glazing or vegetation. In this study most use internal blinds and curtains for solar shading in hot weather, however around a quarter do not (Mavrogianni et al. 2016). In another study, occupants used blinds for solar shading where they were installed, but many did not seek installing blinds as a measure to prevent overheating (Baborska-Narożny et al. 2017). External shading may be resisted by occupants due to them being used to the current aesthetic (Lomas & Porritt 2017). Closing blinds or curtains or the use of shutters may however be undesirable to those who occupy houses throughout the day as it reduces light to the living space. Most windows in the UK open outwards, and as such retrofitting a shutter or shading may mean changing the windows (Richard Partington Architects 2012).

Ventilation may not always be used to cool buildings as assumed. A study of occupants in London found that on a hot day 1 in 10 occupants would not open their windows in the day, and 1 in 5 would not open the windows at night (Mavrogianni et al. 2016). Patterns in window opening and reasons for not opening windows are likely location based (Richard Partington Architects 2012). Occupants will not use windows to ventilate and cool the internal environment if there is excessive noise (Richard Partington Architects 2012; Lomas & Porritt 2017), pollution (Taylor 2014), insects entering, excess pollen, smells, or a security risk (Richard Partington Architects 2012; Taylor 2014). Many occupants only open windows when at home due to security risk (Baborska-Narożny et al. 2017).

2.6 Chapter Summary

There is variation in solid wall dwellings, both in their use of materials and construction technique. In SAP solid walls are assumed to have a U-value of 2.1 W/m²K (DECC 2013). Measurement studies have shown that solid walls perform better than this, with the lowest average U-value across studies of 1.24 W/m²K (Rye & Scott 2012). Measurement studies have also found that the median airtightness of solid wall dwellings is better than expected at 10.1 m³/h.m² (Birchall et al. 2011). However, although measured U-values and air tightness are often better than assumed, solid wall dwellings are still energy inefficient compared to modern buildings and there were no measurement studies found of the whole house heat loss of solid wall dwellings. Solid wall dwellings can be improved using IWI, which is less complex to install and therefore cheaper than EWI and is the only option to improve the walls of some heritage buildings due to planning restrictions. There have been
a few studies of U-values of walls with IWI, however there is little known about the whole house thermal performance of solid wall dwellings with IWI installed. There is an increasing concern about overheating in buildings in temperate climates such as the UK (Lomas & Porritt 2017). Improving the thermal performance of solid wall buildings with IWI could cause them to overheat (Porritt et al. 2012; Gupta & Gregg 2013; Mavrogianni et al. 2012; Ji & Webster 2012). However there have been limited measurement studies on the effect of internal wall insulation on indoor temperatures and overheating, nor the effectiveness of mitigation strategies (DCLG 2012). This thesis sets out to fill these gaps in knowledge.
3 Research design and methods

3.1 Introduction

This chapter outlines the research design, gives an overview of the methods employed and details the materials used in this study. The research was designed to measure the thermal performance, energy demand and overheating risk of a house before and after the installation of internal wall insulation using the most precise, real world method possible (section 3.2). The measurements were conducted in a pair of solid wall test houses (section 3.3). Methods for the measurement of thermal performance (section 3.4) and monitoring (sections 3.5 and 3.6) are described. Appropriate methods were selected for the analysis, normalisation and extrapolation of monitored data (section 3.7); then models were used to identify the performance gap (section 3.8). The instrumentation used to measure the houses is described (section 3.9). The test schedule is given to familiarise the reader with the timeline of the work (section 3.10).

3.2 Research design

The impact of retrofitted wall insulation could be quantified through several different research methods. These methods include the measurements take in test houses, measurements in case-study houses, the measurement of many houses in the housing stock, or a dynamic thermal simulation study. Any of these research methods could be effective for the study of overheating; although there are already several modelling studies and only one measurement study found about overheating in houses with IWI. However, only measurement as a research design could answer the questions of whole house thermal performance or energy demand. In a dynamic thermal simulation, assumed U-values and a perfectly installed system of IWI would be used as inputs; this would not allow for any new knowledge into the true U-values or thermal performance achieved when installing IWI in a real building. It is for this reason that a measurement study was chosen.

3.2.1 A case study using test houses

This research is a detailed study of internal wall insulation. The aim of the study was to investigate the impact of IWI on the thermal performance, energy demand and overheating. Most importantly is how these three areas interact. How does the thermal performance of a building affect its winter energy demand? Could making a building more energy efficient in winter make the building uncomfortably hot for occupants in summer? This interaction meant that the study of all three areas needed to be undertaken in the same house.

To gain an in-depth understanding of how a building retrofitted with IWI performed it was necessary to do pre and post comparisons. A pair of typical houses (see section 3.3) was used as a test facility, and was measured both before and after the installation of IWI, which was commissioned especially for this project. The useful knowledge sought was how much the thermal performance of a building could be improved, how much energy could be saved, and by how much could the overheating risk be increased. Without a baseline, i.e. a ‘typical’
buildings performance, the end point is less meaningful, and offers less transferable knowledge for the rest of the building stock.

An alternative research design was explored, this entailed the less in-depth measurement of a sample of 10-20 houses to draw conclusions on more of the building stock. To make pre-post comparisons houses were required that were uninsulated, but were about to undergo the installation of internal wall insulation. This sample was sought through the largest local insulation installer and advice taken from a major insulation manufacturer. There were at that time no installations of internal wall insulation in homes in that county, or other counties nearby. Further to this, the time and resources in a PhD are limited. It was not possible to find a large randomly selected sample of houses in which to conduct these experiments, which would make the results representative of the building stock. Therefore, a single case study house typical of a large part of the housing stock was used.

### 3.2.2 Measuring thermal performance

Thermal performance was measured to fulfil objective 2. The primary purpose of installing internal wall insulation is to reduce CO₂ emissions by reducing energy demand. To reduce energy demand the thermal performance of the building must be improved, reducing the rate of heat flow from the inside to the outside. The energy demand required to heat a house is dependent on its size, to compare houses independently of their size measures of thermal performance can be used because they are normalised by floor or element area.

Heat loss from a building envelope is often divided into two distinct categories: the infiltration loss and the fabric loss. Infiltration losses are the air escaping directly through small gaps and cracks in the building fabric. The infiltration losses, also known as the air permeability, were measured to find how these were affected by covering the internal face of external walls with insulation. Fabric losses are losses that occur by heat passing through building elements such as the walls or floors, by conduction, convection and radiation. In this project the reduction in thermal transmittance (U-value) of the walls due to IWI was the focus and therefore measured. However it is not possible to measure a whole element and the effect of thermal bridges is not captured in U-value measurement. Further to this, each element i.e. the floors, roof, windows was not measured individually, as they were not being studied and would not change. To capture the heat losses of all elements, the effect of thermal bridging and the infiltration losses altogether the heat loss of the whole house was measured: the heat transfer coefficient (HTC).

### 3.2.3 In-situ monitoring in winter and summer

In-situ monitoring was done in winter and summer to fulfil objectives 3 and 4. To measure the energy demand in winter and the overheating risk in summer, realistic indoor environments are needed. A realistic indoor environment requires occupants, because their metabolic rate and use of electrical devices produces internal heat gains. These internal gains elevate the indoor temperature, therefore less heat is required from the heating system in the winter, and overheating risk is increased in the summer. However, occupants produce irregular gains, occupy the house at irregular times through the day and week, and use devices an irregular
amount. In order to compare a house with and without internal wall insulation, the internal gains needed to be the same. Synthetic occupancy was therefore used (section 3.4), creating regular controllable gains across the experiments. Synthetic occupancy can be used to test the houses’ response for an average set of occupants. However, a limitation of synthetic occupancy in measurement studies is that the impact of a range of occupancy profiles on energy demand and indoor temperatures cannot be investigated.

A house was to be monitored in its uninsulated state, then insulated and monitored again. The pre and post monitoring would therefore be done under different weather conditions, so the results could not be compared directly. To resolve this issue a pair of houses, located next to each other and constructed at the same time were used. The two houses side-by-side meant they could be compared directly to one another when they were uninsulated; this was termed matched pair monitoring, ensuring the houses had the same thermal behaviour prior to the installation of IWI. One of the pair of houses was then internally insulated, and the houses could be compared again in a different time period. These are side-by-side or latitudinal comparisons.

### 3.2.4 Comparing measurements with models

The two houses’ thermal performance and energy demand were predicted using a simple model to fulfil objective 1. When designing the retrofit of a house, a model is used to predict the energy saving using the pre-post HTCs of the building. The HTC of a building is calculated from the air permeability and the elements’ U-values. If the model predicts the pre or post retrofit energy demand poorly, a performance gap between predicted and actual energy saved may be created. Building energy models must be able to correctly predict the energy saving due to IWI to avoid a performance gap.

The measured air permeabilities, U-values, HTCs and the monitored energy demands were compared to modelled values. RdSAP was used to model the houses because it is the Government’s method for assessing the energy demand of domestic buildings (section 3.8). The measured and modelled air permeabilities, U-values and HTCs were compared because they are used as inputs to building energy models; this reveals how well the model predicts with accurate or inaccurate inputs. The measured energy demand was compared to modelled energy demand because this is the final output of the model. The energy demand was predicted using both measured and modelled inputs to show how well the whole model was functioning.

### 3.3 Test Houses

#### 3.3.1 Description of the test houses

A pair of semi-detached, solid wall houses was used to test how the installation of IWI affects thermal performance, energy demand and overheating risk. The houses were located five miles from the Loughborough University campus in the village of Mountsorrel, Leicestershire and are pictured in Figure 3-1. The houses were acquired through the local authority for housing and leased to the university as a research facility for two years. The houses were constructed in 1910 and are typical of many houses of the Edwardian and Victorian periods. The walls of the houses were solid, constructed using a Monk bond (see section 4.4.2)
Figure 3-1: The test houses (Top image: before renovation, Bottom image: prepared for testing)
and were made of brick and mortar, with an internal plaster finish. The roofs of the houses were covered in slate tiles, the floors in the living room were suspended timber, and those of the rest of the ground floor were solid concrete.

The houses were semi-detached, 21% of all solid wall dwellings in England are semi-detached, 41% are terraced, 26% are flats and 8% are detached (DCLG 2017a). Solid wall insulation has the potential to be very effective in reducing energy demand in semi-detached houses because they have three exposed facades. Semi-detached houses can also be considered reasonable proxies for end-terrace properties, which are 11% of all solid wall dwellings in England.

3.3.2 Geometry of the test houses

A building survey was completed where the internal dimensions of the house were measured using a laser measurer both before and after IWI was installed. Floor plans of the houses are presented in Figure 3-2, the houses when viewed from the front are referred to throughout as ‘left’ and ‘right’. The houses each had a floor area of 82m², this is close to the median of floor areas of solid wall dwellings in the 2015 English Housing
Survey data (DCLG 2017a). They were south-southeast facing; the left house when viewed from the front has a large exposed west-southwest facing wall, whereas the right house has a slightly less exposed east-northeast facing wall. Each of the houses had a living room at the front, a dining room in the middle and a kitchen at the back of the ground floor. Upstairs on the first floor there was a main bedroom at the front, a smaller bedroom in the middle and a bathroom at the back of the houses. The right house had a pantry whereas the left did not; the right house also had an additional, small east-northeast facing window in the dining room and no vent in the bathroom.

3.3.3 Preparing the houses for testing

The houses were refurbished to a modern standard, suitable as a base-case, prior to the commencement of the experiments. New uPVC double glazed windows and doors were installed, with 4mm glass panes, a 20mm argon filled gap and a low-e coating, the windows had a U-value of 1.2 W/m²K. The loft was insulated with 300mm of fibreglass insulation, with 100mm laid between the joists and 200mm laid on the top of them, this was to a higher standard than the current building standard of 250mm of insulation (DCLG 2016b). Lastly, an A-rated condensing combination boiler was installed with a 7 day programmable timer and a wireless thermostat. This refurbishment made the houses modern, but not atypical compared to the housing stock; by 2011 52% of solid wall houses had double glazed windows and 47% of all houses had over 150mm of loft insulation (DCLG 2013b). The houses were brought to this modern standard because it is after the installation of double glazed windows and loft insulation that the installation of IWIs would be considered; these other methods are less expensive to install and have faster payback times so would be installed first.

The houses were rewired and reconnected to the gas and electricity networks, much of the houses’ pipework was replaced, and new radiators were installed. The living rooms, dining rooms and all bedrooms were fitted with a nylon carpet with a bonded underlay, the kitchens’ floors were tiled and the bathrooms had vinyl floor coverings. The houses had chimneys in the living rooms, dining rooms and all bedrooms, these were sealed with plasterboard and fitted with a vent in the living rooms and dining rooms. There were also vents in the walls of the kitchens in both houses and the bathroom of the left house.

3.3.4 Internal wall insulation

The internal wall insulation was installed in the left house in March 2015. A metal frame system was mounted onto the wall onto which 50mm of phenolic insulation laminated with 12.5mm of plasterboard: Kingspan Kooltherm produced by Kingspan Insulation Ltd, was affixed (Figure 3-3). This mechanical fixing solution was chosen as it allowed for the easier and less destructive removal of the IWIs in August 2015. As the insulation was to be removed, internal fixings such as skirting boards, coving and the electricity consumer unit were left in place. This is atypical, usually the skirting boards and coving would be removed to allow the metal frame system to be installed as close to the surface of the internal walls as possible and reduce any risk of mould or wood rot and the electricity consumer unit would usually be moved for easy access. Due to the presence of skirting boards, coving and architrave the internal wall insulation was installed with varying air gaps behind it. The joints between the insulation boards were taped and sealed with mastic, however a skim coat of plaster
was not applied. Returns of 0.4m of IWI were installed on the party wall and on the internal partition walls, where they met external walls, to reduce thermal bridging; this is typical of an IWI installation. Existing ventilation ducts on fireplaces and in the kitchen and bathroom were extended through the insulation layer and fitted with grilles.

Figure 3-3: Internal wall insulation installation, metal frame (left) and phenolic boards (right)

3.3.5 Thicknesses of the external walls

Wall thicknesses were measured using a tape measure, before and after IWI was installed, they are displayed in Table 3-1. The thickness of the walls varied significantly across the walls of the houses, with a range in values of 16mm, likely due to varying plaster thicknesses: a new layer of plaster was applied in the right house on several surfaces.

Measurements were taken of the dimensions of the bricks of the external walls of the houses. Bricks produced in 1910 were not manufactured to the same standard sizes as modern bricks and these bricks had weathered considerably, therefore their size is unknown without measurement. Twenty-four measurements of each dimension: length, width and depth, were taken (it was not possible to survey these three dimensions of each brick as access is only possible to access two dimensions of most house bricks that are built into a wall). The average brick size was 229 mm x 110 mm x 77 mm. These are larger than modern bricks; this is not unusual, as noted in the work of Li et al. (2014) most older bricks are longer than 220mm.
Table 3-1: Brick wall thicknesses

<table>
<thead>
<tr>
<th>Location</th>
<th>Thickness of the original brick wall with plaster (mm)</th>
<th>Thickness of the brick wall with plaster plus IWI (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left house by front door</td>
<td>242</td>
<td>242 + 210 = 452</td>
</tr>
<tr>
<td>Left house by gas pipeα</td>
<td>247</td>
<td>247 + 170 = 417</td>
</tr>
<tr>
<td>Left house dining room window</td>
<td>250</td>
<td>250 + 110 = 360</td>
</tr>
<tr>
<td>Left house by back door</td>
<td>241</td>
<td>241 + 140 = 381</td>
</tr>
<tr>
<td>Left house by small bedroom window</td>
<td>249</td>
<td>249 + 80 = 329</td>
</tr>
<tr>
<td>Left house by bathroom window</td>
<td>252</td>
<td>252 + 150 = 402</td>
</tr>
<tr>
<td>Right house by front door</td>
<td>241</td>
<td>-</td>
</tr>
<tr>
<td>Right house by dining room windowβ</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>Right house by small bedroom windowγ</td>
<td>251</td>
<td>-</td>
</tr>
<tr>
<td>Right house by bathroom windowδ</td>
<td>257</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>248</td>
<td>390</td>
</tr>
</tbody>
</table>

αThis wall includes an external layer of render with embedded stone chips
βAll of these walls have an additional layer of plaster

Plaster thicknesses were measured in three different locations in the two houses where there were existing holes from the removal of fixtures. It was possible to measure the thickness of the plaster in two locations in the houses; it was 12mm thick in the left house front bedroom and 13mm thick in the left house small bedroom. A double thickness brick wall with 13mm of plaster applied should be 242 mm in width, as was measured in several places (Table 3-1).

3.4 Methods for measuring thermal performance

The two test houses’ thermal performance was characterised twice, both pre and post IWI installation. This was to meet Objective 2: Characterise the thermal performance. There are several methods that could have been used to measure the thermal performance of the pair of solid wall test houses. The BRE (BRE 2014) collated the methods of measurement of solid wall properties; the methods used by other researchers: co-heating tests, infiltration tests, IR camera surveys and heat flux measurements, have been used as a package in this study. The options and methods chosen for the measurement of air permeability, thermal transmittance and whole house heat loss are described.

3.4.1 Air permeability measurement

Air permeability can be measured to understand the infiltration and ventilation heat losses from houses. There are two main methods of testing: the fan pressurisation test and the tracer gas test (ASHRAE 2002; Johnston et al. 2013). Either test can be performed to measure the infiltration rate alone, or the combined infiltration and ventilation rate. To measure the infiltration rate alone, all purposeful ventilation must be sealed. Fan
Pressurisation tests were used for measuring the air permeability because there is a standard method and the tests for both houses can be done with one set of equipment in one day. The tests were performed twice on each house, pre and post IWI: once to characterise the infiltration losses and once to characterise the combined infiltration and ventilation heat losses.

To perform a fan pressurisation test, often referred to as the blower door test, the building is pressurised or depressurised with a fan. Several differential pressures between the inside and outside are created, these are measured with a corresponding air flow that was required to create each pressure (ATTMA 2010; BSI 2015). A relationship is found between the measured building pressure differential (Pa) and the building air leakage (m$^3$/h) using regression; from this q50 is found: the air permeability in m$^3$/h.m$^2$ at a pressure of 50 Pascal (ATTMA 2010; BSI 2015). This can be divided by 20 to give the number of air changes per hour at ‘normal’ building pressure (DECC 2013).

An alternative to the fan pressurisation test is the tracer gas test, there are two types of tracer gas measurements: the tracer gas decay and the constant tracer gas method (Johnston et al. 2013). Tracer gas measurements are done at normal building pressure, a gas is injected into the building and the rate of decay, or the rate of input of replacement gas is measured. A single tracer gas measurement gives little information about the infiltration rate of a building (BSI 2015), tracer gas measurement should be repeated several times. This is because the tracer gas captures variation in infiltration rate due to wind speed and pressure differential (Jack et al. 2017). Tracer gas appears to be more widely used for analysing the infiltration losses for particular areas of building such as the floor or roof space, or examining different zones (Beizaee 2016; Pelsmakers 2016).

Both the tracer gas method (Blondeau et al. 1997; Jack et al. 2017; Terés-Zubiaga et al. 2015; Pfafferott et al. 2005) and the blower door method (Bell et al. 2010; Beizaee et al. 2015; Loveday & Vadodaria 2013; Johnston et al. 2016; Birchall et al. 2011) are used in building energy studies. The blower door test is recommended for the use of finding the effect of an individual retrofit measure, and has been used in many studies for this purpose (Hong et al. 2004; Stevens & Bradford 2013; Makrodimitri 2010).

Due to the normal building pressure used and the multiple tests, tracer gas tests may be give more accurate results. However, the infiltration rates measured using blower door tests and tracer gas tests are similar (Jack et al. 2017; Patel et al. 2011). The blower door test is more mainstream: its use is mentioned in SAP (DECC 2013), and there is a ISO standard method for the blower door test, whereas there is not for the tracer gas test (BSI 2015). This is likely due to the speed that the blower door offers, compared to tracer gas methods.

3.4.2 Thermal transmittance (U-value) measurement

The thermal transmittance, often referred to as a U-value, of a building element can be measured. There is only one method for measuring an existing building element: the in-situ heat-flux method; there are alternative laboratory methods for elements not in-situ. BS ISO 9869:2013 is the standard method for the in-situ measurement of thermal transmittance (BSI 2014). Measurements of the heat flux through the element, the indoor air temperature and the outdoor air temperature are recorded for three days or longer. The U-
value is the average heat flux divided by the average temperature differential (BSI 2014). The point U-values of the external walls were measured using the in-situ heat-flux method before and after retrofit.

This method measures point U-values: the small area of the element under the heat flux plate. It does not take account of variation that can occur across an element (Pelsmakers et al. 2017). It has been used in many studies of building energy efficiency, with several analysing the effect of wall insulation on U-values (Wright et al. 2012; Currie et al. 2013; Walker & Pavia 2015; Stevens & Bradford 2013).

3.4.3 Whole house heat transfer measurement

A co-heating test is used to measure the whole house heat transfer coefficient (HTC) of a building. This is the combined fabric and infiltration heat losses. Here, the whole house heat transfer coefficient was measured using a co-heating test both before and after the retrofit of IWI. The test is based on a steady-state heat balance, the amount of energy put into the house to sustain an elevated and constant indoor temperature, is equal to the heat lost from the house to the external environment (Johnston et al. 2013). The electrical energy input and the indoor-outdoor temperature differential are measured; regression is performed on these variables and the slope of the line is the HTC. There are also more advanced methods of analysis which take into account gains from solar radiation. There is no ISO standard method for co-heating, however there is a method published by Leeds-Becket University (Johnston et al. 2013), which is the basis for most tests (Jack et al. 2017).

Co-heating tests need to have a long enough duration in order to produce enough varied data to perform regression upon, this period is generally 1-3 weeks (Johnston et al. 2013; Butler & Dengel 2013). Houses must be unoccupied during co-heating due to the elevated temperature and because openings must not be used; this can often make testing impractical (Jack 2015). There are few co-heating test studies in real houses, instead they are often done in test houses (Jack et al. 2017; Beizaee 2016; Butler & Dengel 2013).

3.4.4 Infra-red thermography

Infrared thermography was used as an extra tool to help identify inconsistencies in the building fabric. Infrared thermography is the method of capturing an image of the radiant heat energy being emitted, reflected or passing through building surfaces. The heat image produced is a thermal image (BSI 1999). It is used most often in building energy research to find inconsistencies or air leakage paths in the building fabric (Jack et al. 2017). It is complex to use thermography quantitatively because apparent differences in surface temperature could actually be reflections or differences in emissivity rather than a defect or air leakage (Pearson 2002). To use thermography quantitatively the building materials’ emissivity, reflectivity and absorptivity must be known and so must the temperature of all surfaces the material is reflecting or absorbing energy from; therefore it is often used primarily as a qualitative tool (BRE 2014). There is a British Standard method for infrared thermography: BS EN 13187 (BSI 1999). Infrared thermography has been used qualitatively by researchers to assess retrofitted solid wall installation (Hopper et al. 2012; Gupta & Gregg 2016).
3.5 Method for monitoring the test houses in winter

To fulfil Objective 3: measure the energy demand, the test houses were monitored in winter. Monitoring is the collection of data from a house under normal operating conditions. The houses were synthetically occupied with a profile of a family of four, detailed in Section 3.5.2. The data collected during winter monitoring were gas consumption, heat demand, electricity consumption, indoor air temperatures, outdoor air temperature and solar radiation. The equipment and its locations are detailed in Section 3.9. Gas consumption, heat demand, electricity consumption and solar radiation were measured because these are the heat inputs to the houses. Indoor and outdoor air temperatures were measured because it is the temperature differential that drives heat loss.

3.5.1 Winter monitoring tests

Two tests were done in the winter of 2015 to assess the reduction in energy demand due to the installation of internal wall insulation, an overview can be seen in Table 3-2:

**Winter Test 1: Matched Pair Test**, both houses were in their original state. The test was used to assess the similarity in energy demand between the houses when neither had any insulation. If the energy demand was similar enough any difference between the houses in Winter Test 2 would be entirely due to the IWI.

**Winter Test 2: Left House Insulated Test**, the left house had internal wall insulation applied. This test was used to test the reduction in building energy demand and increase in indoor temperatures due to IWI.

**Table 3-2: Winter test configurations**

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Start Date</th>
<th>End Date</th>
<th>Length of tests (days)</th>
<th>Left house internally insulated?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Test 1: Matched Pair Test</td>
<td>17th February 2015</td>
<td>6th March 2015</td>
<td>18</td>
<td>×</td>
</tr>
<tr>
<td>Winter Test 2: Left Insulated Test</td>
<td>29th March 2015</td>
<td>1st May 2015</td>
<td>33</td>
<td>✓</td>
</tr>
</tbody>
</table>

3.5.2 Winter synthetic occupancy profile

The test houses were unoccupied, there were no internal gains from people and appliances, which would have given an unrealistic indoor environment. Gains were therefore introduced into the houses on schedules, this is
synthetic occupancy. Synthetic occupancy has the benefit over real occupants of being regular for the analysis of data and repeatable across the monitoring tests.

Several measurement and modelling studies in the field of building physics have developed and used occupancy profiles. A standard occupancy profile was developed by the BRE: “Standard dwellings for modelling details of dimensions, construction and occupancy schedules” (Allen & Pinney 1990). Lifestyles and technology have changed considerably over the last twenty-five years therefore modern occupancy profiles were found in academic literature.

Richardson et al. (2008) and Beizaee et al. (2015) used the Time Use survey to produce occupancy profiles for energy demand studies in winter. The United Kingdom 2000 Time Use survey was commissioned by the UK government to understand how people spend their time (ONS 2003; ONS 2006). 6414 households completed diaries at 10 minute intervals; the diary detailed the activity, location, duration of activity and time of day it was undertaken of each participant, (ONS 2003). A follow up survey in 2005 was used to find changes in lifestyle, this produced an extra report detailing duration of activities for different demographics (ONS 2006).

Both Allen and Pinney (1990) and Beizaee et al. (2015) use a family of four profile, with two adults and two children, this was also used here. The work of Beizaee (2015) was combined with further analysis of the 2000 Time Use survey data and information from the 2005 Time Use Survey report to produce the family of four profiles for winter energy demand tests (Table 3-3, Figure 3-4). Two different family profiles were developed for use in winter: a weekday profile and a weekend profile. The weekday profile allowed for intermittent occupancy and the weekend profile for continuous occupancy. Times were shifted for the weekend profile; the Time Use surveys show that people spend more time sleeping on the weekends, having roughly 8 hours in the week and 9 and a half on the weekends (ONS 2006; ONS 2003).
3.5.3 Winter internal gains

Heat gains were introduced into the houses on schedules by switching on and off heat emitting electrical devices. Different electrical devices were required to produce a range of internal gains in different rooms, these included light bulbs rated from 20W-70W, site lights rated at 400W and oil filled radiators rated at 1500W. A smart home controller system: Vera3 (Vera Control 2017), was used to control the heat emitting
electrical devices inside the house; the home controller communicated wirelessly with plugs attached to each electrical device, switching them on and off at the set times dictated by the schedule created.

Internal gains produced by people are dictated by their metabolic rate and affected by their current level of activity. Heat sources to represent these metabolic gains were turned on whenever occupants were scheduled to be in the house and were different for the activities of cooking, standing, sitting and sleeping. Figures for the average metabolic rates for an adult during these activities were found in ASHRAE fundamentals (ASHRAE 2013), and it is recommended that the metabolic rates for a child should be 75% of that of an adult.

Gains from lights, cooking and electronic devices to be used in monitoring were developed in a study by Beizae et al. (2015), from tables published by the ASHRAE (2013). The lighting load was reduced for this project, from 30W to 20W, to take account of low energy bulb use. In this study the family of four profile on weekdays consumed 4.8 kWh, on the weekend consumed 6.7 kWh, a daily average of 5.3kWh; the elderly couple had a daily electricity consumption of 5.5 kWh, detailed gains can be seen in Table 3-3. This electricity consumption was slightly lower than an average UK household. OFGEM has set their typical domestic consumption values between 2000 and 4900 kWh per year, the median of low and high users in the lower and upper quartiles respectively, (OFGEM 2015). This is equivalent to a daily consumption of 5.5kWh-13.4kWh. However it is not simply electricity consumption being represented in the houses, but the heat gains from electrical appliances; electricity used by dishwashers and washing machines are considerable, however much of the heat energy is expelled outside via the drain, therefore these are not included in the gains. The gains used in the test houses in winter are presented in Table 3-3.
Table 3-3: Heat gains for a family of four occupancy profile

<table>
<thead>
<tr>
<th>Room</th>
<th>Time of day: weekday</th>
<th>Time of day: weekend</th>
<th>Source of gains (W)</th>
<th>Total gains required (W)</th>
<th>Heat sources used</th>
<th>Total gains used (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living Room</td>
<td>16.00-17.30</td>
<td>17.30-18.30</td>
<td>Adult seated: 108</td>
<td>278</td>
<td>70W bulb *3</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>10.00-17.30</td>
<td>Television: 150</td>
<td></td>
<td>60W light bulb *1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19.30-23.00</td>
<td>19.30-23.00</td>
<td>Adult seated: 108*2</td>
<td>386</td>
<td>70W bulb *4</td>
<td>382</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Television: 150</td>
<td></td>
<td>42W bulb *1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lighting: 20</td>
<td></td>
<td>60W light bulb *1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Adult seated: 108*2</td>
<td>386</td>
<td>70W bulb *4</td>
<td>382</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Television: 150</td>
<td></td>
<td>42W bulb *1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lighting: 20</td>
<td></td>
<td>60W light bulb *1</td>
<td></td>
</tr>
<tr>
<td>Dining Room</td>
<td>8.00-8.30</td>
<td>9.30-10.00</td>
<td>Adult seated: 108*2</td>
<td>396</td>
<td>400W double tripod</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>18.30-19.30</td>
<td>18.30-19.30</td>
<td>Child seated: 80*2</td>
<td></td>
<td>400W double tripod</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lighting: 20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td>7.30-8.00</td>
<td>9.00-9.30</td>
<td>Adult cooking: 189</td>
<td>429</td>
<td>400W tripod</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>17.30-18.30</td>
<td>17.30-18.30</td>
<td>Cooking: 160</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lighting: 20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.00-17.30 18.30-7.30</td>
<td>9.30-17.30 18.30-7.30</td>
<td>Fridge: 60</td>
<td>1869</td>
<td>1500W oil filled 400W tripod</td>
<td>1900</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adult’s bedroom</td>
<td>23.00-7.00</td>
<td>23.00-8.30</td>
<td>Adult sleeping: 72*2</td>
<td>144</td>
<td>70W bulb *2</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>7.00-7.30</td>
<td>8.30-9.00</td>
<td>Adult Sleeping: 72</td>
<td>72</td>
<td>70W bulb *1</td>
<td>70</td>
</tr>
<tr>
<td>Children’s bedroom</td>
<td>16.00-18.30</td>
<td>10.00-18.30</td>
<td>Children seated: 80*2</td>
<td>280</td>
<td>60W bulb * 4</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>19.30-20.30</td>
<td>19.30-20.30</td>
<td>Lighting: 20</td>
<td></td>
<td>20W bulb * 2</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Computer: 100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20.30-23.00</td>
<td>20.30-23.00</td>
<td>Child seated: 80</td>
<td>200</td>
<td>60W bulb * 3</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lighting: 20</td>
<td></td>
<td>20W bulb * 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Computer: 100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>23.00-8.00</td>
<td>23.00-9.30</td>
<td>Children sleeping: 54*2</td>
<td>280</td>
<td>60W bulb * 4</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20W bulb * 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60W bulb * 2</td>
<td>100</td>
</tr>
<tr>
<td>Bathroom</td>
<td>7.00-8.00</td>
<td>8.30-9.30</td>
<td>Adult standing: 126</td>
<td>146</td>
<td>60W bulb * 2</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>19.30-20.30</td>
<td>19.30-20.30</td>
<td>Lighting: 20</td>
<td>115</td>
<td>60W bulb *2</td>
<td>120</td>
</tr>
</tbody>
</table>
3.5.4 Central heating profile

There are recommended indoor temperatures and heating durations given in CIBSE guide A and the Standard Assessment Procedure (CIBSE 2006; DECC 2013). However this study’s purpose was to test a normal house and standards have been proven to be different to the way real people run their houses (Kane et al. 2015). The central heating profile was therefore developed using the most recent literature concerning people’s actual behaviour in their homes.

A study by Kane et al. (2015) analysed the heating patterns and indoor temperatures in winter from 249 dwellings in Leicester. It was found that there was no significant difference between the heating patterns of weekdays and weekends. This could be largely owing to a lack of control as many homes do not have 7 day timers installed. Further to this the study found that 33% of houses had one heating period per day and 51% of houses had two heating periods; two heating periods were chosen for this study as this was the most prolific. The median heating times for a pre-1919, solid wall semi-detached house with a double heating period were: 6:00-9:00 and 15:00-22:00, a total of 10 hours per day (Kane et al. 2015). This was used as the heating profile in the test houses on weekdays and weekends.

The mean of the maximum temperatures in solid wall houses was 20.4 ºC, which indicates an average set point of 20.5 ºC (Kane et al. 2015). The thermostat in the test houses was therefore set to 21 ºC; this is also the recommended heating temperature in RdSAP. The thermostatic radiator valves (TRVs) were set to a slightly lower output temperature in the bedrooms to achieve the lower average bedroom temperature of 17.4 ºC from Kane et al. (2015).

It has been found in many studies that people change their energy demand habits after renovation of a house (Makrodimitri 2010; Hong et al. 2006), often by increasing the indoor temperature. This is known as the take-back effect, whereby people heat their homes more, enjoying higher temperatures and improved thermal comfort, and save significantly less energy than expected. This was not included in these tests because it was necessary to compare the energy savings of IWI independently of this effect. Therefore the same set-point temperatures and heating profiles were used in both Winter Test 1 and Winter Test 2 for consistency.

3.5.5 Winter blind and window use

During the winter energy demand tests the blinds were kept closed continuously in the south-southeast facing rooms to shield the instruments from low direct solar radiation. Solar gains are small in winter, so contribute minimally to the internal gains and therefore indoor temperatures. The blinds remaining closed reduced differences in solar gains between the two winter monitoring tests. Winter Test 1: Matched Pair Test took place between 17th February - 6th March 2015, when there was less solar radiation; and the Winter Test 2: Left Insulated Test took place between 29th March 2015 - 1st May 2015, when there was more solar radiation. The windows in both houses were continuously closed throughout winter testing.

63
3.6 Method for monitoring the test houses in summer

To fulfil Objective 4: measure the overheating risk and the effectiveness of a mitigation strategy, the houses were monitored in summer. The houses were synthetically occupied to run as if continuously occupied by two elderly residents, detailed in Section 3.6.2. The data collected in summer was indoor air temperatures, black globe temperature, air velocity, surface temperatures, electricity consumption, outdoor air temperature and solar radiation. The equipment and its locations are detailed in Section 3.9. Indoor air temperatures, black globe temperature, air velocity, surface temperatures were measured to calculate operative temperature. Operative temperature is the mean of air temperature and mean radiant temperature, at an air velocity of less than 0.1 m/s (CIBSE 2013); it better represents the experience of people in a room due to including both air and radiant temperatures (BSI 2005). Mean radiant temperature can be significantly higher than air temperature during hot weather (Walikewitz et al. 2015), therefore operative temperature is a suitable variable to assess overheating. Electricity consumption and solar radiation were measured because they were the gains increasing the indoor temperature. Outdoor air temperature was measured for use alongside the indoor temperature to calculate the temperature differential, which drives heat loss.

3.6.1 Summer monitoring tests

Three tests were performed in the summer of 2015; an overview can be seen in Table 3-4:

**Summer Test 1: Left House Insulated Test**, the left house was internally insulated. The test was used to quantify the increase in indoor air temperature due to IWI and whether the overheating risk increased. Both houses had their windows closed at all times and the blinds were open in the day but closed at night from 10pm to 8am the following morning, further described in Section 3.6.4.

**Summer Test 2: Mitigation Test**, the left house was insulated and a simple and low cost mitigation strategy was applied. The purpose of this test was to establish whether high indoor air temperatures could be avoided through the use of a mitigation strategy. Modelling studies have shown that a mitigation strategy consisting of solar shading and night ventilation have the potential to reduce overheating risk (Porritt et al. 2012; Mavrogianni et al. 2014). To limit solar gains the blinds in the south-southeast oriented living room and main bedroom remained closed throughout the day and night. To implement a night-ventilation strategy the upstairs windows were opened at night, detailed in Section 3.6.4. Blinds were used for solar shielding and the windows for ventilation because these would be present in most homes and could offer a simple, low cost method of mitigation for most occupants.

**Summer Test 3: Matched Pair Test**, both houses were uninsulated. This test used to discover whether the houses could be considered to respond the same as one another to warm outdoor air temperatures and solar radiation; this test was used to validate the differences seen in Summer Test 1. I.e. were the differences seen due to the internal wall insulation, or was the left house warmer due to it having a large south-west facing external wall, which could absorb significant solar gains throughout the day whereas the right did not. During this test both houses had the same window and blind configuration as Summer Test 1: their windows closed at
all times and the blinds were open in the day but closed at night.

Table 3-4: Summer test configurations

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Start Date</th>
<th>End Date</th>
<th>Length of tests (days)</th>
<th>Left house internally insulated?</th>
<th>Mitigation Strategy Applied?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer Test 1: Left House Insulated Test</td>
<td>5\textsuperscript{th} June 2015</td>
<td>3\textsuperscript{rd} July 2015</td>
<td>29</td>
<td>✔</td>
<td>✕</td>
</tr>
<tr>
<td>Summer Test 2: Mitigation Test</td>
<td>11\textsuperscript{th} July 2015</td>
<td>31\textsuperscript{st} July 2015</td>
<td>21</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Summer Test 3: Matched Pair Test</td>
<td>19\textsuperscript{th} August 2015</td>
<td>8\textsuperscript{th} September 2015</td>
<td>21</td>
<td>✕</td>
<td>✕</td>
</tr>
</tbody>
</table>

3.6.2 Summer synthetic occupancy profiles

As for the winter monitoring, an occupancy profile was also required for summer. From the Time Use Survey (ONS 2003; ONS 2006) Porritt (2012) developed two summer occupancy profiles. One of a family consisting of two adults and school age children, who leave the house in the day and are at home in the evening; another of

![Elderly Couple Profile](image)

Figure 3-5: Summer elderly couple synthetic occupancy schedules
an elderly couple, over the age of seventy, who stay in the house throughout the day and evening. These were developed for use in dynamic thermal models to model summer overheating, and were built summer occupancy data.

An elderly couple may feel the strongest effects of overheating because they are present for the hottest part of the day (Porritt 2012). A recent monitoring study found that overheating occurs more often in homes occupied by vulnerable residents (Vellei et al. 2016). Therefore an elderly couple profile was produced for use in the summer overheating tests (Figure 3-5). The elderly couples profile stayed constant throughout the week.

3.6.3 Summer internal gains
The same system of the smart home controllers and heat emitters used in the winter (Section 3.5.3), was used to control the internal gains into the houses in summer. The same metabolic and electrical appliance gains were used as in the winter study (Section 3.5.3). In summer the elderly couple had a daily electricity consumption of 5.5 kWh, detailed gains can be seen in Table 3-5.
<table>
<thead>
<tr>
<th>Room</th>
<th>Time of day</th>
<th>Source of gains (W)</th>
<th>Total gains required (W)</th>
<th>Heat sources used</th>
<th>Total gains used (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living Room</td>
<td>16.00-17.30</td>
<td>Adult seated: 108, Television: 150, Lighting: 20</td>
<td>278</td>
<td>70W bulb *3, 60W light bulb *1</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>08.30-17.30</td>
<td>Adult seated: 108*2, Television: 150, Lighting: 20</td>
<td>386</td>
<td>70W bulb *4, 42W bulb *1, 60W light bulb *1</td>
<td>382</td>
</tr>
<tr>
<td></td>
<td>19.30-23.00</td>
<td>Adult seated: 108*2, Television: 150, Lighting: 20</td>
<td>386</td>
<td>70W bulb *4, 42W bulb *1, 60W light bulb *1</td>
<td>382</td>
</tr>
<tr>
<td>Dining Room</td>
<td>8.00-8.30</td>
<td>Adult seated: 108*2, Lighting: 20</td>
<td>236</td>
<td>60W bulb *4</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>18.30-19.30</td>
<td>Adult seated: 108*2, Lighting: 20</td>
<td>236</td>
<td>60W bulb *4</td>
<td>240</td>
</tr>
<tr>
<td>Kitchen</td>
<td>7.30-8.00</td>
<td>Adult cooking: 189, Cooking: 160, Lighting: 20, Fridge: 60</td>
<td>429</td>
<td>400W tripod</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>17.30-18.30</td>
<td>Adult cooking: 189, Cooking: 1600, Lighting: 20, Fridge: 60</td>
<td>1869</td>
<td>1500W oil filled, 400W tripod</td>
<td>1900</td>
</tr>
<tr>
<td></td>
<td>8.00-17.30 18.30-7.30</td>
<td>Fridge: 60</td>
<td>60</td>
<td>60W light bulb</td>
<td>60</td>
</tr>
<tr>
<td>Adult’s bedroom</td>
<td>23.00-7.00</td>
<td>Adult sleeping: 72*2</td>
<td>144</td>
<td>70W bulb *2</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>7.00-7.30</td>
<td>Adult Sleeping: 72</td>
<td>72</td>
<td>70W bulb *1</td>
<td>70</td>
</tr>
<tr>
<td>Children’s bedroom</td>
<td>- -</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Bathroom</td>
<td>7.00-8.00</td>
<td>Adult standing: 126, Lighting: 20</td>
<td>146</td>
<td>60W bulb *2, 20W bulb</td>
<td>140</td>
</tr>
</tbody>
</table>
3.6.4 Summer blind and window use

Light grey coloured roller blinds were fitted in the south-southeast facing rooms only and were controlled using a motor on a timer. There is little literature on normal blind use. Allen and Pinney (1990) detail blind use, recommending they are closed from 17:00:08:00 each day; however this does not appear to be based upon the actions of real people. There was little research available on the opening and closing schedules of window coverings based on real people at the time the study was designed, therefore reasonable assumptions were used to develop a blind strategy. These assumptions were that blinds were opened in the morning when occupants were finished getting ready for the day and that blinds were closed when it got dark outside. Based on the occupancy schedules blinds were opened daily at 8.00am and closed at the average sunset time in summer: 10.00pm. The sun set between 7.30pm (on 11th September) and 9.32pm (on the 25th June) through the summer monitoring period, at 10pm the twilight was sure to have finished. The blinds were open and shut on this set schedule throughout Summer Test 1: Left House Insulated Test and Summer Test 3: Matched Pair Test. For Summer Test 2: Mitigation Test the blinds were closed constantly as part of the mitigation strategy to limit solar gains.

The windows remained closed throughout Summer Tests 1 and 3, but were opened for Summer Test 2 as part of the mitigation strategy to offer night ventilation. This night ventilation was to purge the warm air from the house, replacing it with cool air at night. Several studies (Mavrogianni et al. 2012; Porritt et al. 2012; Porritt et al. 2011; Tillson et al. 2013) focus on opening windows at set indoor operative temperature thresholds; this is unrealistic because it does not represent the way people in homes use windows (Vellei et al. 2016). Windows were instead opened on a set schedule, from 5.30pm each evening and closed at 8am the following morning for one month. It is believed that occupants would not want to open all of their windows due to a perceived security risk, this risk was also present in the unoccupied test houses. Therefore for realism of the tests and for security of the houses, only the top floor, top light windows were opened. The windows were opened to 45°; the measured free area provided by these openings for both houses was 0.51 m² in the main bedroom, 0.29 m² in the second bedroom and 0.24 m² in the bathroom. The windows in the bathroom and smaller bedroom were oriented north-northwest, while the main bedroom window was oriented south-southeast; these window’s opposite orientations ensured cross ventilation and therefore an improved night purge of air.

3.7 Analysing monitoring data

The test houses were a pair of semi-detached houses, built together in around 1910 (Section 3.3). The thermal performance tests; Winter Test 1 and Summer Test 3 (matched pair tests) were used to provide evidence to how thermally matched the houses were. If the houses were thermally matched when they both had no insulation, the houses could then be compared directly to one another in Winter Test 2, Summer Test 1 and Summer Test 2, when the left house had IWI, and any difference observed between the houses in a test period would be due to the IWI. Side-by-side analysis could therefore be used to assess:

- The energy saving due to IWI during the test period of Winter Test 2.
- The increase in indoor operative temperature due to IWI during the test period of Summer Test 1.
• The difference in indoor operative temperature between a house with and without IWI, **both with a mitigation strategy applied**, in Summer Test 2.

Side-by-side analysis could not be used to assess:

• The energy saving due to IWI in a different month or a **typical year**.
• The increase in operative temperature during a **typical or future summer year**.
• The **effectiveness of the mitigation strategy** in reducing operative temperature in a house with IWI.

Therefore models were required to normalise and extrapolate the winter measured data into a typical heating season, and the summer measured data into a design summer year. Further to this the model was needed in summer to allow a cross-test comparison between Summer Test 1 and Summer Test 2 to analyse the effect of the mitigation strategy. Different types of simple models can be used to simplify a complex system, options and the justification of the models chosen is in section 3.7.4.

Arguably, a different research design could have been done to find the answers not provided by side-by-side analysis. The tests could have been extended to an entire year; however, this would still have had the limitation that the year could be exceptionally hot or cool. To reduce the need for a cross-model comparison both houses could have been insulated with IWI and one mitigated; but this would have added significant cost to the project.

Presented below are the methods of side-by-side analysis, the models used to normalise and extrapolate the data, the method used to validate them, and the forecasting done.

3.7.1 Side-by-side data analysis of winter monitoring data

A side-by-side comparison has the simplicity of no manipulation of a set of data which was carefully collected with known uncertainties. However, despite the care of data collection there were some differences in the internal conditions of the houses during testing, resulting in different indoor air temperatures and applied synthetic occupancy; these factors in addition to the different orientations of the houses meant they were matched but not identical, results are formally presented in Chapters 5.

Total heat gains and losses were produced from the measured data to compare the differences between the left and right houses in each test period. The heat gains were the sum of the measured central heating demand, gains from people and appliances and the solar gains in each period. The central heating demand was measured directly and the gains from people and appliances were measured directly: this was electricity consumption (section 3.9). The solar gains were calculated from measured solar radiation using the method in the RdSAP (DECC 2013).

The heat losses were calculated using Equation 5, using measured average indoor air temperature, measured average external air temperature and the measured heat transfer coefficients.
\[ Q_L = U'(\bar{T}_i - \bar{T}_o) \]  

(Equation 2)

\[ U' = \text{heat transfer coefficient (including fabric, infiltration and ventilation heat transfer)} \]
\[ \bar{T}_i = \text{average indoor air temperature} \]
\[ \bar{T}_o = \text{average external air temperature} \]

3.7.2 Side-by-side data analysis of summer monitoring data

Operative temperatures were used to assess overheating in the houses because they better represent the experience of occupants; further theory and the calculation method is described in Section 2.4.1. To compare the houses within each testing period descriptive statistics were produced of indoor operative temperatures, in the living room and main bedroom, the outdoor air temperature and the horizontal solar radiation in all three tests. The statistics for indoor operative temperature were calculated for the assumed ‘occupied’ hours, which were set as 08:30 to 23:00 in the living rooms and 23:00 to 07:30 in the main bedrooms. Occupied hours were used because outside of these hours there would be no-one to experience the temperatures, it would not matter if unoccupied rooms overheat. Outdoor air temperature statistics have also been produced for these time periods to show the temperature of the air driving heat loss and in the case of the mitigation tests the temperature of air entering the bedroom at night.

The Mean Absolute Difference (MAD) has been used in each test to enumerate the difference between the two houses (Equation 3). The MAD sums the differences in temperature at each time step, regardless of direction between the two houses i.e. the difference is counted whether the left or right house is warmer.

\[ \text{Mean Absolute Difference} = \frac{\sum_{i=1}^{n} |x - y|}{n} \]  

(Equation 3)

The average daily indoor operative temperature range, the ‘swing’ in operative temperature, was calculated in each test, swing was defined as the difference between the maximum operative temperature that occurred on each day and the minimum operative temperature that was recorded over the next 18 hours. This allowed for an assessment of how the internal wall insulation affected the swing, which has a relationship to the thermal mass of the building.

3.7.3 Assessing overheating

Overheating was analysed in the living rooms using the CIBSE TM52 (2013) method and in the bedrooms using static CIBSE Guide A criteria (2015a). CIBSE TM52 was chosen because it has a dynamic overheating criteria and guidance on how to assess measured data; this is the most appropriate for assessing comfort in homes where adaptive opportunities are available. Since the completion of the work CIBSE TMS9 was released, which gives better guidance on assessing overheating in homes, but is focussed on modelling rather than assessing measured data.
The CIBSE TM52 (2013) method recommends three criteria, of which, if two are failed, then overheating occurs:

**Criterion 1**: Hours of exceedance; the indoor operative temperature cannot exceed the threshold temperature, $T_{\text{max}}$ (seen in Figure 3-6 at the I, II and III categories) by more than 1 °C for more than 3% of occupied summer hours.

**Criterion 2**: Daily weighted exceedance; the number of hours the indoor operative temperature exceeds the threshold temperature, weighted by the severity of the temperature difference. The value must not exceed 5 °Ch on any one day.

**Criterion 3**: Upper limit temperature; a total unpassable value for comfort.

<table>
<thead>
<tr>
<th>Category</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.</td>
</tr>
<tr>
<td>II</td>
<td>Normal level of expectation and should be used for new buildings and renovations An acceptable, moderate level of expectation and may be used for existing buildings.</td>
</tr>
<tr>
<td>III</td>
<td>An acceptable, moderate level of expectation and may be used for existing buildings.</td>
</tr>
<tr>
<td>IV</td>
<td>Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.</td>
</tr>
</tbody>
</table>

*Figure 3-6: Indoor comfort temperature as a function of exponentially weighted running mean outdoor temperature of the previous day (BSI 2007b)*
The threshold temperature upon which the criteria are based is the comfort temperature plus an acceptable range of temperature depending upon the expectations of the occupants of the building. The comfort temperature, from CIBSE TM52 (2013) is defined as:

\[ T_{comf} = 0.33 T_{rm} + 18.8 \]  
(Equation 4)

Where:
- \( T_{comf} \) is the comfort temperature (°C)
- \( T_{rm} \) is the exponentially weighted running mean outdoor temperature of the previous day (°C), from CIBSE TM52 (2013) defined as:

\[ T_{rm} = (1 - \alpha)(T_{t-1} + \alpha T_{t-2} + \alpha^2 T_{t-3} + \alpha^3 T_{t-4} + \alpha^4 T_{t-5} + \alpha^5 T_{t-6} + \alpha^6 T_{t-7}) \]  
(Equation 5)

Where:
- \( T_t \) is the mean outdoor air temperature on day \( t \) (°C)
- \( \alpha = 0.8 \)

Threshold temperature \( T_{max} \) as defined in CIBSE TM52 (2013) is:

\[ T_{max} = T_{comf} + CF \]  
(Equation 6)

Where:
- \( T_{max} \) is the threshold temperature (°C)
- \( CF \) is a category factor of:
  - \( \pm 2^\circ C \) for spaces occupied by very sensitive and fragile persons of ‘high expectation’ (Category I)
  - \( \pm 3^\circ C \) for new builds or renovations considered a ‘normal expectation’ (Category II)

As defined in CIBSE TM52 (2013), Equation 7 is used to calculate the severity of overheating detailed in criterion 2.

\[ W_e = (\Sigma h_e) \times WF \]
\[ = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) \ldots \]  
(Equation 7)

Where
- \( W_e \) is the weighted exceedance
- \( WF \) is the weighting factor, \( WF = 0 \) if \( DT \leq 0 \), otherwise \( WF = \Delta T \), and
- \( h_{e0} \) is the time (h) when \( WF = 0 \)

These adaptive comfort criteria are believed to be suitable for rooms in dwellings where adaptive opportunities are available (BSI 2007b; CIBSE 2013); however CIBSE (2015a) cautions against the use of the new adaptive comfort criteria for assessing overheating in bedrooms because occupants have limited adaptive
opportunity while in bed. Instead, CIBSE Guide A (2015a) recommends that a fixed operative temperature threshold of 26 °C should not be exceeded, unless there is a means for creating air movement (CIBSE 2015a). The previous version of CIBSE Guide A (2006) provided guideline benchmark summer peak temperatures and overheating criteria for bedrooms, whereby they would be classed as overheating if 1% of annual occupied hours exceeded an operative temperature of 26 °C; this criteria can only be used in situations where a whole year of data is available. Therefore here in this study, the fixed threshold temperature of 26 °C from CIBSE Guide A (2015a) was used and overheating was assessed to occur when 3% of measured occupied hours exceeded the threshold; this was to match the 3% of hours exceedance in CIBSE TM52 (2013) criterion 1.

3.7.4 Methods for normalising and extrapolating measured data

A model was sought for the normalisation and extrapolation of the daily measured energy demand data into a full year of energy demand data. Another model was sought to normalise measured hourly indoor operative temperatures to allow a comparison of Summer Tests 1 and 2; to extrapolate the data to assess overheating in a standard year of data; and to extrapolate the data to predict overheating under future weather scenarios. Hourly operative temperature was sought because overheating is assessed on an hourly basis. The simplest models which would achieve these predictions were sought, as per Occam’s Razor.

There were a wide range of models that could have been used for these purposes. Mathematical models can be categorised in many different ways, one of these is whether they are physics-driven (white-box model), data-driven (black-box model) or hybrid (grey-box model). Definitions are taken from Reddy (2011):

**White-box models** are mechanistic, they calculate outputs from physical knowledge of the system; an example is Dynamic thermal simulation. Dynamic thermal simulation can be verified or calibrated using measured data, however this is generally not very successful (Reddy 2006).

**Black-box models** are purely data driven, relationships of any type are found between the input and output variables, there is no structure to the system; an example is regression modelling.

**Grey-box models** are a hybrid of black and white models, model structures are loosely defined using physical principles, data is then used to determine the model parameters.

Grey and black-box models were sought because they can be data driven. Academic literature was reviewed to find suitable methods.

A commonly used grey-box model for the normalisation of energy demand data is the degree-days method (Day 2006). It is the primary method of normalising measured energy demand data from buildings as seen in the work of Beizaee et al. (2015), Corgnati et al. (2008), Hong et al. (2006) and Thomsen et al. (2016). Changes in a building’s energy demand can be identified using the degree-days method, in this case the change in energy demand due to the retrofit of internal wall insulation. The benefits of the method are its speed of use and its transparency when compared to a dynamic thermal simulation; the inputs are limited but transparent.
(Day 2006). Degree-days analysis was therefore trialled as a method of normalising and extrapolating the energy demand of the houses.

Another method for the normalisation of daily energy demand is regression. This has also been used by several researchers to create models of energy demand in buildings (Cho et al. 2004; Fels 1986; Katipamula et al. 1998). This can be done at the daily or hourly time scale (Katipamula et al. 1998), there is less scatter found in daily or monthly averaged values, rather than on an hourly or less time resolution (Katipamula et al. 1998). Some models use a single variable of outdoor temperature to predict winter energy demand (Cho et al. 2004), whereas others use multiple predictor variables (Fels 1986; Katipamula et al. 1998; Ruch & Claridge 1992). One study achieved an annual energy prediction within 6% of measured values using outdoor temperature as a single predictor (Cho et al. 2004). The multiple predictor methods can be purely statistical, black-box models; alternatively they can be hybrid-models, fixing the form of the predictor variables using physical principles (Katipamula et al. 1998; Fels 1986; Ruch & Claridge 1992).

Other methods are also used to model energy demand such as artificial neural networks and support vector machines, however these are highly complex to implement (Zhao & Magoulès 2012). Regression was chosen as the method of data extrapolation for winter because it is appealing in its simplicity and can be used for identifying energy savings from retrofit (Katipamula et al. 1998). Multivariate linear regression can offer a much better r squared value than single variable regression for modelling energy consumption in buildings (Katipamula et al. 1998), therefore both single and multivariate modelling was trialled.

To normalise and extrapolate hourly operative temperature data another model was sought. Hourly indoor temperatures have a time-lagged relationship to the outdoor temperature, heat inputs, and a relationship to the hourly indoor temperature at the previous time step. There have been many different types of models used to predict indoor temperature in free running buildings including lumped parameter models (Kramer et al. 2013; Terés-Zubiaga et al. 2015; Tindale 1993), ARIMA and ARMAX models (Loveday & Craggs 1993; Iddon et al. 2015) and Artificial Neural Networks (Pandey et al. 2012). However many of these models required months of training data (Iddon et al. 2015; Kramer et al. 2013), which was not available in this project. Others only predicted a short time step into the future, e.g. 1 hour (Loveday & Craggs 1993). Or it was unclear from methods the amount of training data required, the predictive time, the validation method, or the final accuracy of the model (Kramer et al. 2013; Terés-Zubiaga et al. 2015; Tindale 1993; Pandey et al. 2012). This led to the conclusion that there are currently no accurate models that can be trained using hourly indoor temperature from a free running building and make accurate predictions.

Simpler models were sought as an alternative, which would predict daily indoor temperature instead of hourly indoor temperature. Coley and Kershaw (2010) have shown that the indoor temperature of a free-running building has a linear relationship to external temperature, in their work using dynamic thermal simulation. Therefore simple forecasts can be made of indoor temperature using external temperature.
Several studies from the literature show that linear regression can be used to accurately predict indoor temperatures in free running dwellings, therefore they have been used in this project to normalise and extrapolate summer indoor operative temperature data. Givoni and Vecchia (Givoni & Vecchia 2001), predicted daily indoor minimum and maximum temperatures using external temperature, achieving $R^2$ values of 0.83 and 0.91; the model of daily maximum temperature was improved marginally by the inclusion of solar, improving the $R^2$ by 0.05. Krüger and Givoni (2004) predicted internal maximum, average and minimum temperatures in occupied, free running dwellings in Brazil. External daily maximum, average and minimum temperatures were used in multiple linear regression as predictors; their regression models yielded $R^2$ values ranging from 0.94-0.99. They included solar as a multiple regression variable, but these yielded minimal improvement in $R^2$ value. Krüger and Givoni (2008) predicted internal maximum, average and minimum temperatures in a passive house in Israel. Outdoor air temperature, outdoor running average temperature, maximum outdoor air temperature, minimum outdoor air temperature, outdoor air temperature range, two day outdoor air temperature range, effective solar, occupancy factor were used as predictor variables in multiple linear regression. In summer $r^2$ values between 0.71-0.93 were achieved, when the formulas were validated against data from a different time period $r^2$ values between 0.72-0.92 were achieved.

3.7.5 Degree-Days modelling
The degree-days method can be used in two ways: as a deterministic, white-box, model to predict energy demand for a building yet to be built using assumptions; or as a grey-box model, a model with partial structure and some data input, to analyse the energy demand of existing buildings from measured data. Here it was used as a grey box model.

The method of using degree-days is described here and is taken from CIBSE TM41 (Day 2006). Degree-days quantify the duration and magnitude of the temperature difference between the outdoor temperature ($T_o$) and a reference temperature known as the baseline temperature ($T_b$) Figure 3-7; degree-days are then used to calculate fuel consumption using Equation 7. The most accurate method of calculating degree-days is to find the difference between $T_b$ and $T_o$ hourly then to average these values into daily degree-days, Equation 8. Only positive differences are summed, when the outdoor temperature is less than the baseline temperature. Daily degree-days can then be summed into monthly or yearly values.
Figure 3-7: Definition of Degree-Days, the average difference between the baseline temperature and the outdoor air temperature

\[ F = \frac{24 \ U' D_d}{\eta} \]  \hspace{1cm} (Equation 8)

Where:
- \( F \) = fuel consumption
- \( \eta \) = seasonal heating system efficiency
- 24 converts from days to hours

\[ D_d = \frac{\sum_{j=1}^{24} (T_b - T_o_j)^+}{24} \]  \hspace{1cm} (Equation 9)

Where:
- \( D_d \) = degree-days
- \( T_b \) = baseline temperature
- \( T_o \) = outdoor temperature

The baseline temperature (\( T_b \)) is the outdoor temperature at which no input from the heating system is needed. At the baseline temperature the indoor air temperature is maintained at or above the heating systems set-point temperature by solar gains and gains from people and appliances. \( T_b \) is calculated using the average indoor air temperature, the utilisable gains and the heat transfer coefficient, Equation 9.

\[ T_b = \bar{T}_i \left( \frac{Q_o}{U'} \right) \]  \hspace{1cm} (Equation 10)

Where:
- \( \bar{T}_i \) = average indoor air temperature
- \( U' \) = heat transfer coefficient
- \( Q_o \) = corrected gains
For use in Equation 9 gains must be corrected by a utilisation factor, detailed by Day (2006), taken from BS EN ISO 13790 : 2004:

\[ Q_G' = \eta' Q_G' \]  
(Equation 11)

Where \( \eta' \) is the gains utilisation factor:

\[ \eta' = \begin{cases} 
1 - \gamma^a & \text{if } \gamma \neq 1 \\
\frac{1}{a+1} & \text{if } \gamma = 1 
\end{cases} \]  
(Equation 12)

\[ \eta' = \frac{a}{a+1} \]  
(Equation 13)

Where:

\( a = 0.5 \), due to the intermittent operation of the heat system of the building.

\( \gamma = \) gains to losses ratio

The gains to losses ratio is calculated using Equation 13:

\[ \gamma = \frac{Q_G'}{Q_L} \]  
(Equation 14)

Where:

\( \gamma = \) gains to losses ratio

\( Q_G' = \) Uncorrected gains

\( Q_L = \) losses

Measured heat demand in each house can then be normalised by finding heat demand per degree-day for the house in question, then multiplying this by the degree days of the other house, Equation 14.

\[ H_2 = H_1 \left( \frac{D_{d,2}}{D_{d,1}} \right) \]  
(Equation 15)

Where

\( H_2 = \) heat demand in period 2

\( H_1 = \) heat demand in period 1

\( D_{d,1} = \) degree-days of period 1

\( D_{d,2} = \) degree-days of period 2

The method can be used at different timescales; the most common timescale as described by Day (2006) is monthly; this timescale is used due to its ease and limited computations. However, calculating a daily baseline temperature from daily indoor air temperatures and gains has been shown to be more accurate than on a monthly temporal basis (Day & Karayiannis 1999). A daily method was employed here, using no assumptions,
only measured data of internal and external temperatures, heat demand, solar gains, gains from people and appliance and, HTCs.

3.7.6 Linear regression modelling

Regression is the process of building a model using the least squares method. This method often referred to as finding the ‘line of best fit’, is the process of finding the model with the smallest residuals, between the measured data and the model. The model is built to predict the dependent variable, using one or more independent variables. Once this relationship between dependent and independent variables is found the model can be used to predict the outcome of dependent variables not in the dataset.

Linear regression is used when the relationship between variables are known to be linear. Models can be produced using one predictor variable: single regression, or two or more predictor variables: multiple regression. A multiple linear regression model is of the form:

\[
y = (m_1x_1 + m_2x_2 + \cdots + m_nx_n + c) + \varepsilon
\]

(Equation 16)

Where:
\(y\) = dependent variable
\(x\) = independent variable
\(m\) = coefficient of independent variable
\(c\) = intercept
\(\varepsilon\) = error

The \(m_nx_n\) pair of terms is for each independent variable, in single regression only one pair of terms is present.

Dependent and independent variables were systematically trialled alone as a single regression model and with other independent variables as a multiple regression model. The ‘goodness of fit’ of each of these regression models were assessed and ranked using \(R^2\). This assessment is based upon the improvement of this model compared to the most basic model of the data – the mean. It represents the amount of variance in the dependent variable that can be explained by the model.

Assumptions were checked in order to use the multiple regression models built on a sample of data (days) to predict outcomes of a whole population (a whole year). These assumptions taken from Field (2009), are:

- Variable types
- Non-zero variance
- No perfect multicollinearity: Average 0.5 < VIF < 1.5
- Predictors are uncorrelated with external variables
- Homoscedasticity
- Independent errors:
- 1 < Durbin-Watson < 3
• Normally distributed errors
• Independence
• Linearity

Satisfying assumptions was part of the model building process, whereby models that severely violated these models were not selected, and a model with similar predictive power ($R^2$) but that met the assumptions were chosen instead.

In winter the best possible model was sought to predict the amount of central heating required. The dependent variables trialled were:

**Central Heating Demand**

**Total Internal Gains** (Central Heating Demand + Gains from people and appliances)

**Total Heat Gains** (Central Heating Demand+ Gains from people and appliances +Solar Gains)

Both directly measured and calculated independent variables were trialled to produce a model to predict the dependent variables. Those calculated mathematically produce a hybrid statistical-mathematical model whereby the independent variable can constitute several variables that have a non-linear relationship to the dependent variable or a desired fixed form. The independent variables trialled to predict heat demand were:

**Outdoor Air Temperature (°C)** – measured (Section 3.9.3).

**Horizontal solar radiation (W/m²)** – measured (Section 3.9.3).

**Solar gains (kWh)** – calculated from solar radiation using the method detailed in RdSAP (DECC 2013).

**Siviour solar gains (kWh)** – calculated using the method detailed in 0

**Gains from people and appliances (kWh)** – measured (Section 3.9.3).

**Heat loss (kWh)** – calculated, using Equation 5.

**Exponentially weighted outdoor running mean temperature**: $T_{wo}$ (°C) – Equations 16 and 17. The exponentially weighted outdoor running mean temperature is a measure of the outdoor air temperature on day $t$, but also includes the outdoor air temperatures of past days, $t_1$, $t_2$ etc.; it is an established method of time series analysis (Reddy, 2011). It is particularly useful for buildings because it takes into account the effect of thermal mass, where a change in outdoor temperature has a lagged effect on indoor temperature. $\alpha$ provides a weighting of today compared to past days. It has a relationship to the characteristics and use of the building, such as its thermal mass and thermal resistance. A building with little thermal mass and low thermal resistance will require a lower alpha value that puts a significant weighting upon the present. An alpha that best represented the thermal characteristics of each house in each test was found statistically through single regression before it was used as a part of a multiple regression.

$$T_{wo} = (1-\alpha)T_t + \alpha T_{wo-1}$$  \hspace{1cm} (Equation 17)

79
Where:

- $T_t$ = the mean outdoor air temperature on day $t$
- $\alpha$ = a constant relating to the thermal mass of the building
- $T_{WO}$ = the exponentially weighted outdoor running mean temperature, initially calculated using:

$$T_{WO} = (1 - \alpha)(T_t + \alpha T_{t-1} + \alpha^2 T_{t-2} + \alpha^3 T_{t-3} \ldots)$$  \hspace{1cm} (Equation 18)

Indoor temperature was not included as a predictor variable in the regression because it controls the amount of heat consumed directly due to the thermostat; therefore indoor temperature and gas use are highly correlated and can both be predicted by external temperature solar irradiation and occupancy gains. The variables would have multicollinearity, which is undesirable in regression. This is difficult as it would be helpful to be able to control for indoor temperature to compare two houses at different temperatures. Independent and dependent variables were never used twice in the same regression.

In summer a model was sought to predict daily average indoor operative temperature from daily outdoor environmental conditions. A study by Krüger and Givoni (2008) built successful models of indoor air temperature using the independent variables of; outdoor air temperature, outdoor running average temperature, maximum outdoor air temperature, minimum outdoor air temperature, outdoor air temperature range, two day outdoor air temperature range, effective solar, occupancy factor. As many of these were highly successful in explaining the variance in indoor air temperature many were trialled as predictors, plus any other data thought possible to explain variance. The independent variables trialled to predict indoor operative temperature were:

- **Outdoor Air Temperature ($^\circ$C)** – measured (Section 3.9.3).
- **Maximum Outdoor Air Temperature ($^\circ$C)** – calculated from measured outdoor air temperature.
- **Minimum Outdoor Air Temperature ($^\circ$C)** – calculated from measured outdoor air temperature.
- **Outdoor Air Temperature Range ($^\circ$C)** – calculated from measured outdoor air temperature.
- **Two Day Outdoor Air Temperature Range ($^\circ$C)** – calculated from measured outdoor air temperature, temperature drop on the current day from the previous day’s outdoor maximum.
- **Horizontal Solar Radiation (W/m$^2$)** – measured (Section 3.9.3).
- **Vertical Solar Radiation (W/m$^2$)** – calculated on a south facing facade from measured horizontal solar radiation (Section 3.9.3) using the method detailed in RdSAP (DECC 2013), but with solar declination at solar noon in the location of the houses.
- **Wind Speed (knots)** – data from a BADC weather station at Sutton Bonington (Section 3.9.3).
- **Relative Humidity (%)** – data from a BADC weather station at Sutton Bonington (Section 3.9.3).
- **Rainfall (mm)** – data from a BADC weather station at Sutton Bonington (Section 3.9.3).
- **Exponentially weighted outdoor running mean temperature ($^\circ$C)** – calculated from measured outdoor air temperature using Equations 16 and 17 above.
3.7.7 Validating models

Models were tested to ensure that they could provide accurate predictions. This was done by validating models built on data from the right house, in order to build models for the left house. This is known as data splitting and has been used by Krüger and Givoni (2008) when using linear regression models to predict indoor temperatures. This process was used for the winter monitoring data because it was to be used to predict other values. Data-splitting was used to validate both the Degree-Days models and the linear regression models. The process is outlined below and visualised in Figure 3-8.

Step 1: The right house data were split into two parts; that from the Winter Test 1 (R1 data) and Winter Test 2 (R2 data). Models were built on both of these sets of data and then used to predict the heat demand in the other time period, testing the prediction performance of the model. Models using predictors that provided the smallest prediction errors for the right houses were identified. The models’ ability to produce correct longitudinal predictions, predictions through time, of the heat demand of the right house was used as a proxy for the validity of the left house models. It was not possible to test the left house models because the left house had IWI installed in the Winter Test 2: Left House Insulated Test.

Step 2 Models were built on the data collected from the left house. Data from the left house was split into that of the Winter Test 1: Matched Pair Test (L1) and Winter Test 2: Left House Insulated Test (L2), models were built on both sets of data then used to predict the heat demand of the other time period. The grey boxes in Figure 3-8 represent the house in its alternative state during each time period. The model built on the data from the Winter Matched Pair Test, predicted the heat demand of the left house during Winter Left House Insulated Test if the house had not been insulated, and vice versa. A side-by-side comparison could then be made between the left house in the same time period in both an insulated and uninsulated state. The models could also be used to predict annual energy demand.
3.7.8 Forecasting

The data collection took place in a random year that was convenient to the researchers, which could have had very typical or atypical characteristics. It could have been an exceptionally warm year that underestimated the energy demand and overestimated overheating risk, or an exceptionally cool year that did the opposite. It was therefore important to predict annual energy demand and summer operative temperatures of ‘normal’ years.

A Test Reference Year (TRY) was used as the means for normalising energy demand. TRYs are produced by CIBSE (CIBSE 2016) and are used when modelling buildings and for Building Regulation Compliance. External temperature and solar radiation from a CIBSE Test Reference Year (TRY) for Nottingham was used within the regression model to predict energy demand for the TRY. The heat demand was calculated only for the months January-May and October-December; this is considered the normal heating season.

To analyse summer monitored data, recent weather was used to normalise indoor operative temperatures, and future weather data were used to extrapolate the data to assess future overheating risk. Recent measured weather data from the previous ten years to the study: 2006-2015 was acquired from the British Atmospheric Database Centre (BADC) weather station at Sutton Bonington (Section 3.9). These data were used to calculate average indoor operative temperatures over this ten year period and assess the percentage of time that the mitigation strategy would have been successful in lowering indoor temperatures.

Under a changing climate it is not simply the current weather conditions that need to be used for assessing overheating risk, but those that are likely to occur in the future. In order to predict the indoor operative
temperature under future, warmer, summers hourly temperature data from the UKCP09 weather generator ‘medium emissions’ scenario were produced for two thirty year periods: 2036-2065 and 2066-2095. Spatially, the weather data is generated based upon a 5km² grid square, the test houses’ location was chosen. The weather generator returns 100 probabilities of outdoor air temperature for each 30 year period, an average of these is the most likely to occur. These data were used to produce exponentially-weighted outdoor running mean temperatures for each day of the 30 years and the 100 probabilities that are given. The median was calculated across the 100 probabilities, producing a single T_{wo} value for each day of summer, for 30 years. The summers only were analysed, from May-September, as this is when overheating is likely to occur and was the period the regression models were built on.

### 3.8 Modelling building performance and energy demand

There are many models that could have been used to predict the thermal performance and energy demand of the test houses. These include annual benchmarking techniques, degree-days methods, quasi-steady state methods and dynamic thermal simulation techniques; these methods are described in detail in CIBSE Guide A (CIBSE 2015a). In this project, the focus is on the measured thermal performance and energy demand of houses before and after solid wall retrofit of insulation. Annual benchmarking techniques are not detailed enough to compare measured data to, so degree-day methods are being employed to normalise measured data (section 3.7.5). One quasi-steady state model is The Government’s Standard Assessment Procedure for Energy Rating of Dwellings (SAP) (DECC 2013). SAP is the National Calculation Method for assessing the energy demand of domestic buildings; to calculate the monthly energy demand it first calculates buildings’ air permeabilities and HTCs. Dynamic thermal simulation is a superior method for calculating the energy demand of dwellings because it calculates over a shorter time scale, usually hourly. This allows for the more realistic representation of fabric heat storage effects and the influence of solar gains, among other benefits.

Reduced data SAP (RdSAP) is used to produce energy ratings for existing buildings where less information is known about construction. Although not intended for this purpose, RdSAP may be used in the decision making process when deciding to retrofit buildings, particularly due to the recommendations for retrofit provided on Energy Performance Certificates (EPCs). Any performance gap between measured and RdSAP modelled energy demand needs to be identified, due to RdSAP’s influence on the retrofit industry. Dynamic thermal simulation is used more rarely when planning the retrofit of a home, due to the expense of modelling for a small project, therefore has less direct impact on the retrofit industry. For this reason, RdSAP has been chosen as a modelling technique for calculating air permeabilities, heat transfer coefficients and energy demand.

There is an ISO standard method recommended for calculating the thermal transmittance of elements (BSI 2007c), and is used in the design and certification of insulation products. This method is therefore used here to calculate the thermal transmittance of walls. These methods are used to fulfil Objective 1: Predict the thermal performance.
3.8.1 Using RdSAP to predict air permeability, HTC and energy demand

The Government’s Standard Assessment Procedure for Energy Rating of Dwellings (SAP) (DECC 2013) is the UK Government’s method of assessing the energy performance of dwellings. It was developed by the Building Research Institute, based on their BREDEM model, and conforms to BS EN ISO 13790 (DECC 2013; BSI 2008). The primary purpose of SAP is to calculate an energy cost rating and an environmental impact rating for buildings, both of which are normalised by floor area. This allows for an energy assessment comparison to be made that is independent of dwelling size. RdSAP is also used in research, predicted energy demand has been compared to measured energy demand of solid wall houses (Birchall et al. 2011; Gupta & Gregg 2016), and a performance gap was found. There have been no comparisons between RdSAP and houses with IWI.

Reduced data SAP (RdSAP) is used to assess the energy performance of existing dwellings, where a complete set of data for a SAP calculation is not available. RdSAP is the same calculation as SAP but instead uses default values and makes inferences based on the buildings age. RdSAP models were produced of both houses when uninsulated and the left house with IWI applied. Inputs to RdSAP include: the internal floor areas and room heights; window and door sizes and orientations; the number of vents and flues and structural ventilation rates; the thermal transmittance and thermal storage capacity of all building elements; the type of hot water system, the heating system and heating controls; and the type of energy used to heat the property.

The air permeability rate of the houses was calculated in RdSAP; it does this by estimating the effects of purposeful ventilation and of structural infiltration. Ventilation includes the air flow from open chimneys, open flues, intermittent fans, passive vents and flueless gas fires. The structural infiltration is calculated by identifying the wall and floor constructions, stating how many stories the dwelling consists of, whether or not the windows and doors are draught stripped and whether there is a draught lobby. This is used in the SAP calculation with how sheltered the houses are and the local wind speed each month to calculate the heat loss due to infiltration and ventilation.

The whole house heat transfer coefficient (HTC) of the houses was calculated in RdSAP by estimating the areas and U-values of all thermal elements including the walls, floors, roof, doors and windows. Values for the transmittance of different thermal elements were taken from RdSAP reference tables for houses built between 1900 and 1929. The areas and U-values are then multiplied together to give the heat transfer in W/K for each element. Each elements U-value is added together to give a fabric heat loss, then a thermal bridging factor is added to give the total fabric heat transfer. The whole house heat transfer coefficient is calculated by adding the losses from the fabric and the ventilation.

To calculate building energy demand two types of RdSAP models were produced. Firstly, ‘Typical RdSAP’ models were produced using the RdSAP calculated air permeabilities and HTCs. Secondly, ‘improved RdSAP’ models were produced using measured air permeability values from blower door tests and U-values from in-situ heat-flux measurements. Using measured values in the models removed some of the uncertainty from using standard assumptions, theoretically producing more accurate models. This allowed for an assessment of whether inaccuracy of energy demand prediction is due to the inputs of the model or the model itself.
3.8.2 Calculating thermal transmittances

When doing RdSAP calculations assumed U-values based on age are generally used. These assumed values have been proven in several recent studies to be incorrect (Baker 2011; Hulme & Doran 2014; Birchall et al. 2011; Li et al. 2014; Rye & Scott 2012; Stevens & Bradford 2013) due to a misunderstanding of solid wall construction and the identification of a micro-cavity (Li et al. 2014). Thermal transmittance of the walls pre and post IWI installation was therefore calculated using BS EN ISO 6946 (BSI 2007c). If the materials and the construction of a wall is known then calculating U-values is very reliable (Rhee-Duverne & Baker 2013). U-values of the solid brick walls of the houses were calculated three times: without a micro-cavity; with a micro-cavity; with a micro-cavity and IWI installed.

Thermal resistance is calculated for any layer or part layer in an element construction using Equation 18. The thermal resistances of air gaps, the internal surface resistance and the external surface resistance are all taken from reference tables in CIBSE Guide A (CIBSE 2015a). The U-value calculation for an element consisting of homogenous layers is different to that of an element composed of bridged layers.

\[ R = \frac{d}{\lambda} \]  
(Equation 19)

Where:
R is the thermal resistance
\( d \) is the thickness of the material
\( \lambda \) is the thermal conductivity

The U-value of a wall consisting of homogenous layers is calculated using Equation 19. This method was used to calculate the U-value of solid brick walls, where the effect of bridging the bricks by plaster is ignored because the difference in the thermal resistances of the mortar and the brick was less than 0.1 m²K/W (CIBSE 2015a).

\[ U = \frac{1}{R_{si} + R_1 + R_2 + R_2 + \ldots + R_{se}} \]  
(Equation 20)

Where:
U is the thermal transmittance
\( R_{si} \) is the internal surface resistance
\( R_{se} \) is the external surface resistance

The U-value of a wall consisting of bridged layers is calculated using Equation 20 by combining the lower and upper limits of resistance. Where the lower limit of resistance in calculated using Equation 21, and the upper
limit of resistance is calculated using Equation 22. This method was used to calculate the thermal transmittance of the brick wall with micro-cavities and the brick wall with micro-cavities and internal wall insulation applied.

\[ R_b = \frac{1}{2} (R_L + R_U) \]  
\text{(Equation 21)}

Where:
- \( R_b \) is the average resistance of the wall
- \( R_L \) is the lower limit of resistance
- \( R_U \) is the upper limit of resistance

\[ R_L = R_{se} + R_1 + \left( \frac{1}{\frac{R_m}{R_{m2}} + \frac{R_n}{R_{n2}} + \frac{R_p}{R_{p2}}} \right) + R_3 + \ldots + R_z + R_{si} \]  
\text{(Equation 22)}

Where:
- \( R_{se} \) and \( R_{si} \) are surface resistances
- \( R_1-R_z \) are unbridged layers of the construction
- \( P_m, P_n, P_p \) are the proportions of the surface area of each material in the bridged layer
- \( R_{m2}, R_{n2}, R_{p2} \) are the resistances of each material in the bridged layer

\[ R_U = \left( \frac{\frac{P_m}{R_{se} + R_{m2} + (R_1 \ldots + R_z) + R_{si}}} + \frac{P_n}{R_{se} + R_{n2} + (R_1 \ldots + R_z) + R_{si}} + \frac{P_p}{R_{se} + R_{p2} + (R_1 \ldots + R_z) + R_{si}} \right)^{-1} \]  
\text{(Equation 23)}

Values of thermal conductivity for the bricks and mortar were taken from CIBSE Guide A (CIBSE 2015a). Masonry materials density and whether they are exposed or protected dictates which values of thermal conductivity are chosen for the calculation; a higher moisture content within a brick increases thermal transmittance (CIBSE 2015a). Exposed values were used because the masonry was exposed to rain. The average density for mortar and the measured density for the bricks, were used to identify the correct thermal conductivity. The values for thermal conductivity for the insulation and metal frame system were supplied by manufacturer.

### 3.9 Instrumentation

The instrumentation used for the measurement of thermal performance, energy demand and overheating are detailed in this section. The measurement of energy demand (section 3.9.1), the indoor environment
(section 3.9.2), weather data (section 3.9.3) are relevant for both winter and summer monitoring. The system of data logging is relevant to the measurement of thermal performance, energy demand and overheating (section 3.9.4).

3.9.1 Energy demand measurement

There are statutes to dictate the accuracy of electricity and gas meters for domestic properties (WEIGHTS AND MEASURES The Measuring Instruments (Gas Meters) Regulations 2006; WEIGHTS AND MEASURES The Measuring Instruments (Active Electrical Energy Meters) Regulations 2006): electricity meters should be accurate to $\pm 0.5\%$ and gas meters between $\pm 2\%$. It was decided the equipment used should be at least as accurate as these. Tampering with gas and electricity supplies in order to record data is dangerous, therefore any equipment used needed to be non-invasive.

LED pulse loggers: Enica Opti-pulses (Enica n.d.) were used to measure whole house electricity consumption at 5 minutely intervals. The electricity meter had an LED output, which pulsed for every 0.001 kWh of electricity consumed. The LED pulse logger had a sensor that was placed over the electricity meters LED and had the capacity to record LED flashes as often as 7 per second. The pulse logger was perfectly accurate if positioned correctly to capture all LED pulses, therefore whole house electricity consumption data had an uncertainty of $\pm 0.5\%$. The capturing of pulses was checked by comparing the electricity meters consumption to that recorded on the logger at the end of each test.

The electricity consumed through each socket was also recorded using electricity loggers: EOL Ploggs. These were individual loggers that plugged into wall sockets and in turn had devices plugged into them. These were already owned by the university so did not need to be purchased especially for the project. The devices were used for recording the actual power consumption of the synthetic occupancy equipment instead of relying on calculated values.

Gas was only consumed through the use of the heating system, as hot water was not used during tests. Secondary gas meters were installed next to the boiler in each test house; it was not possible to use the primary gas meter because it is illegal to tamper with it. The secondary gas meters provided a pulse for every 0.01 m$^3$ of gas consumed which was recorded using the data loggers: DataTaker DT85 (DataTaker 2017). This was in turn converted into kWh in data post processing using Equation 23.

$$G_{kWh} = \frac{(G_m^3 \times C. F. \times CV)}{3.6} \quad \text{(Equation 24)}$$

Where:

- $G_{kWh}$ = Gas in kWh
- $G_m$ = Gas in cubic meters
- C.F. = the correction factor of 1.022640
- CV is the calorific value of gas, over the period of the study this was 39.5
3.6 is the conversion into kWh

The heat output from the boiler was also measured, this meant the quantity of heat provided to the houses were known, without relying on the gas consumption and the changeable efficiency of the boiler. Heat meters: Sontex Superstatic 440 (Sontex 2017) were used, which conforms to the accuracy requirements detailed in BS EN 1434-1 (BSI 2007a). The temperatures of the water entering and leaving the boiler were measured using the heat meters pair of temperature sensors plumbed into the inflow and outflow pipes; the pressure of the water leaving the boiler was measured using the fluid oscillator flow meter. The temperature sensors and the flow meter were connected to an integrator: Sontex Supercal 531 (Sontex 2017) which calculated the heat energy added to the water every 3 seconds and provided a pulse out for every 10Wh of heat energy the boiler provided.

3.9.2 Indoor environment sensors

Air temperature, mean radiant temperature, air velocity and surface temperatures were measured in the houses.

Air temperature was measured during the winter monitoring tests: the Winter Matched Pair Test and the Winter Left House Insulated Test; during the co-heating tests; and during air permeability tests. During winter monitoring the air temperatures were used to analyse the energy demand data by evaluating whether the two houses were heated to similar temperatures. During co-heating tests and air permeability tests the air temperature was measured to find the difference between internal and external temperature, which is part of the analysis procedure.

Air temperature, mean radiant temperature, air velocity and surface temperatures were all measured during the summer monitoring tests. These measured variables were used to calculate operative temperature. Operative temperature represents how a person feels in a space due to the air temperature, mean radiant temperature and the air velocity (BSI 2005). Air velocities of 0.1 ms\(^{-1}\) or below make little difference to the comfort of humans, therefore the velocity term can be omitted in the calculation of operative temperature (CIBSE 2013). Measured air velocity did not exceed 0.1 ms\(^{-1}\) during the tests and therefore the operative temperature was calculated using the mean radiant temperature and the measured indoor air temperature (Equation 25).

\[
T_o = T_{mr} + T_a
\]

(Equation 25)

Where:

- \(T_o\) is the operative temperature (°C)
- \(T_{mr}\) is the mean radiant temperature (°C)
- \(T_a\) is the air temperature (°C)
Mean radiant temperature was both measured directly and calculated from surface temperatures using the human heat exchange by radiation method (CIBSE 2007). In this method the radiant exchange between a person in a space and the surrounding surfaces is calculated from the respective view factors and surface temperatures. The indoor air temperatures were the mean of the air temperatures at 0.1m, 0.6m and 1.1m in the living room, and those measured at a height of 0.6m in the main bedroom.

The sensors used for capturing indoor environmental data conformed to BS EN ISO 7726:2001 (BSI 2001b), which details the equipment to be used when measuring thermal comfort variables. The sensors used to measure environmental variables were:

- **Air temperature**: Thermistors (Grant 2014), accurate to +/- 0.2 °C. Sensors were screened from radiant heat transfer.
- **Mean radiant temperature**: Black globe thermometers: Swema 05 (Swema 2014), accurate to +/- 0.1 °C.
- **Air velocity**: Omnidirectional anemometers: Dantec 54T21 (Dantec Dynamics 2017), accurate to 0.05 m/s, response time of <0.5s.
- **Surface temperature**: T type surface mounted thermocouples (TC Direct 2014), accurate to +/- 1 °C.

The uncertainty of the instruments that collected data were combined using summation in quadrature to give a combined standard uncertainty of ±0.9 °C for the operative temperature from surface temperatures. The calculated mean radiant temperatures from surface temperatures were compared to measurements from black globe thermometers and were found to be within ±0.9 °C 99% of the time. This was considered to be very close considering the inherent uncertainty in measuring mean radiant temperature using a black globe, which can be up to ±5 °C (BSI, 2001).

Prior to the installation in the test houses all instrumentation was checked to ensure that it was in good working order. Thermistors, black globe thermometers, anemometers and thermocouples were all calibrated to ensure they met the accuracy requirements in BS EN ISO 7726:2001 (BSI 2001b). The equipment was calibrated while plugged in to the data loggers to measure the compound effect of the system, not that of the individual sensor and logger.

The thermistors, black globe thermometer and thermocouples were calibrated in a temperature controlled water bath. Sensors were placed into the stirred water bath, and a UKAS calibrated mercury thermometer was used to measure the temperature of the water Figure 3-9. Parsons (2003) recommends this method because it gives an absolute check on each sensor and allows for a relative check between the sensors. Calibration was carried out both before and after testing, to allow for drift with time, as also recommended by Parsons (2003).

The anemometers were calibrated by BSRIA to ±0.05 m/s. Of the eight anemometers used five were within ±0.05 m/s, better than the (0.05 + 0.05v\text{\textsubscript{sk}}) m/s specified by BS EN ISO 7726:2001, (BSI 2001b). The remaining
three anemometers were marginally outside of tolerance, therefore their outputs were modified in the using calibration factors produced using lines of best fit of expected and received values.

Air temperature was measured throughout the winter tests, the co-heating tests and the air permeability tests in the volumetric centre of every room in both houses. The thermistors used to measure air temperature in every room were elevated to the volumetric centre point of each room using camera tripods (Figure 3-10). The thermistors were attached to the tripods using cable ties, and were shielded from radiant exchange with the rooms’ surfaces using a ring of aluminium foil; this allowed air flow to the sensor, was reflective of radiant heat and had minimal thermal mass.

Figure 3-9: Calibration of black globe thermistors (left) and thermistors and thermocouples (right)
Figure 3-10: Shielded air temperature sensor

For the analysis of summer overheating the living rooms and main bedrooms were instrumented with operative temperature stations and surface temperature sensors because the most used areas of the house should be measured (BSI 2007b). Operative temperature stations (Figure 3-11) were created by attaching air temperature, mean radiant temperature and air velocity sensors to plasterboard poles using retort stand clamps. The test rigs were positioned in the rooms in the likely place of an occupant (BSI 2001b). The air temperature sensors and air velocity probes were positioned at three different heights in the living rooms: 0.1m, 0.6m and 1.1m from the floor; this was to capture the variation in the vertical plane due to localised drafts and air stratification that would be experienced by a sitting person (BSI 2001b). Mean radiant temperature in the living room and all three variables in the bedrooms were measured only at the middle height: 0.6m, as this is the height of a person lying on a bed. In the living room the operative temperature station was placed where the middle of a sofa would be, in the centre of the back wall 50cm from it (Figure 3-12). In the main bedroom, the thermal comfort station was placed where it was likely for there to be a bed; this was in the centre of the chimney breast, double beds are 190cm long, therefore the station was placed in the centre of the ‘bed’ 95cm from the chimney breast (Figure 3-12).
Figure 3-11: Operative temperature station

The surface temperature sensors were placed on the walls, floor and ceiling of the living room and main bedroom in summer. The surface temperature across a wall is not consistent; therefore four sensors were distributed evenly across each surface. When placing the thermocouples an infra-red camera was used to check for hot and cold spots on the wall as was done by Historic Scotland in their study (Currie et al. 2013), to ensure representative points were being measured. The thermocouples were attached to the walls and ceiling by creating a small groove in the plaster for them to be placed, applying heat flux paste to ensure good thermal contact then covering with a layer of clear tape (Figure 3-13). The thermocouples on the floor were pushed into the pile of the carpet and covered with tape.
3.9.3 Weather station

Outdoor air temperature was measured next to the north-northwest facing facade of the houses, over 1m from the external walls of the houses, to ensure air temperature not house temperature was measured. Air temperature was measured using a thermistor with an uncertainty of ± 0.2 °C placed inside a solar radiation
shield. The temperature was measured at the site of the houses as there can be local variations. Solar irradiance was measured eight kilometres away at another university test house, it is sufficient to measure it within twenty kilometres (Duffie & Beckman 1991), using a pyranometer: produced by Zipp and Konen, with an uncertainty of 10%. Other weather variables including wind speed, wind direction, humidity and precipitation were all collected by a Met Office weather station in Sutton Bonington, 13 kilometres from the houses, the data were accessed through the British Atmospheric Database Centre.

3.9.4 Data storage

Monitoring was the longest type of test, whereby environmental variables in the houses were measured for at least three weeks. A data collection and storage system needed to be able to be left unsupervised for several weeks. Internal and external air temperature, air speed, humidity, wall surface temperatures, gas consumption and heat demand were recorded every 5 minutes, this time period was short enough to capture change, but not so short as to result in excessive repeated measurements. All data were measured using wired sensors and the data were recorded and stored using data loggers: DataTaker DT85’s (DataTaker 2017). This was suitable within these houses as they were unoccupied, therefore the presence of significant amounts of wiring was not disruptive. This method of data collection was optimal because a wired system is less likely to have communication issues compared to wireless systems. Four data loggers were used, which were placed in the living room and main bedroom of each house; each had 48 analogue input channels, and a memory of 128 Mb which was calculated as sufficient for the tests.

3.10 Test schedule

Figure 3-14 displays the test schedule for all of the tests described above. For each experimental period the top bar represents the right house and the bottom bar represents the left house; further to this the figure is colour coded to show when the left house was insulated.

The co-heating tests and air permeability test are labelled, however the U-value tests are not because they occurred during the Winter Matched Pair Test and the Winter Left House Insulated Test. During the Winter Matched Pair Test and the Winter Left House Insulated Test winter energy demand was being measured. During Summer Test 1: Left House Insulated Test, the Summer Test 2: Mitigation Test and the Summer Test 3: Matched Pair Test summer overheating was being measured. The suffix to each test name e.g. Matched Pair Test, indicates the state of the insulation in the houses.
3.11 Chapter Summary

A pair of unoccupied, semi-detached, solid wall houses was prepared and used as a test facility to measure the effect of internal wall insulation on thermal performance, energy demand and overheating. All tests were done on the houses in their original state then repeated once the left house of the pair was retrofitted with internal wall insulation. The air permeabilities, wall U-values and heat transfer coefficients of the houses were measured to understand their thermal performance, this is summarised in section 3.2.2 and the results are presented in 4. The energy demand, indoor, and outdoor temperatures were measured in winter, the method is given in section 3.5 and the results are presented in Chapter 5. Indoor and outdoor temperatures were measured in summer to assess overheating risk, the method is given in section 3.6 and the results are presented in Chapter 6. Simple models were produced to predict the houses thermal performance and energy demand of the houses, section 3.8, in order to quantify the performance gap.
4 The impact of IWI on thermal performance

4.1 Introduction

The purpose of this chapter is to verify whether the houses were a matched pair, to find out whether the thermal performance of the left house changed with IWI, and to identify any performance gap between measurements and models. The two houses’ thermal performances were characterised both before and after the installation of IWI in fulfilment of Objective 2. A pressurisation test was used to measure the air permeabilities of the houses (section 4.2). Point U-values of the walls were calculated from measured heat fluxes and indoor and outdoor temperatures to quantify the performance of the walls (section 4.2). A co-heating test was conducted to quantify the whole house heat loss coefficients (section 4.2). The left and right houses’ uninsulated measured air permeabilities (section 4.3), U-values (section 0) and HLCs (section 4.5) were compared to each other to ascertain the extent to which the houses were a matched pair. The left house’s air permeabilities, U-values and HLCs measured with and without IWI were then compared to quantify the effect of IWI. Lastly all air permeabilities, U-values and HLCs were calculated, to fulfil Objective 1, and compared to measurements to identify any performance gap.

4.2 Measuring thermal performance

4.2.1 Air permeability

The houses’ air permeabilities were measured using the Building Regulation recommended blower door method (DCLG 2016a) from The Air Tightness Testing and Measurement Association (ATTMA 2010). The houses were left to cool after other tests so that the air density was as similar as possible indoors and outdoors. All tests were carried out on days of low wind speed; a stable outdoor pressure is required to achieve a stable pressure differential while testing. Two air permeability tests were done in each house, in each state of retrofit, the Type A test: to measure the combined ventilation and infiltration rate, and a Type B test: to measure the infiltration rate alone. All vents were closed or sealed using tape for the Type B test, all vents were opened for the Type A tests including air bricks, those on chimney breasts and trickle vents on windows.

The test procedure is as follows: the front door of the house was opened then sealed using a metal frame with a canvas over it, and a large fan was mounted inside a hole in the canvas; the fan was used to create a pressure differential between the internal and external environments. This pressure differential and the amount of air to produce this pressure were measured using a pressure and flow gauge. The building was depressurised to a maximum of 80Pa, the fan speed was then reduced in steps, down to a minimum pressure of 20Pa, with data from 10 pressures collected in total. A blower door system: a TEC Minneapolis (The Energy Conservatory 2017) was used to perform the air permeability tests (Figure 4-1); it was calibrated prior to the tests in January 2015.
The blower door manufacturer’s software: TEC Tectite (The Energy Conservatory 2017) was used to log the pressure differential and the air flow required to produce each pressure differential. Regression was performed, whereby the measured building pressure (Pa) was plotted against building air leakage (m$^3$/h) and a line of best fit was found. From the line of best fit q50 is found, the air permeability in m$^3$/h.m$^2$ at a pressure of 50 Pascal. This is then divided by 20, as in RdSAP (DECC 2013), to give the number of air changes per hour.

Figure 4-1: Experimental setup of air permeability test

4.2.2 U-values

The method detailed in BS ISO 9869-1:2014 (BSI 2014) was followed to measure U-values, using heat plates and flat plate thermocouples: both Hukseflux (Hukseflux 2017) with a wireless data receiver and logger system: Squirrel (Grant 2017). This wireless system allowed for fewer wires to run across the house and none to pass between the inside and outside, reducing security risks. It was a newly bought system for this project, and was therefore newly calibrated. Data was transmitted to the receiver from the heat flux plates every five minutes, then received and stored temporarily by the receiver. The wireless system only allows for one communication at a time, if several transmitters communicate simultaneously does not record any information. The receiver logged the data permanently every 30 minutes, using the most recent data it had in its temporary memory.

The house was surveyed to find suitable places to measure U-values. It was desirable to find walls where two heat flux plates could be placed, one above the other, to measure thermal transmittance in two places on one
wall to achieve a representative average of the total wall and highlight possible differences in U-value due to height. There were very few walls in the house where this was possible, as most external walls have windows, doors, services or chimney breasts upon them. Four suitable walls in each house were identified: one living room wall, one dining room wall, one pantry wall and one kitchen wall; these spanned the whole length of the house (Figure 4-2). An infrared camera was used to assess the wall for homogeneity, insuring the sensors would be positioned on brick wall with plaster, not on imbedded wood. An example of this is in Figure 4-3, on the left there is an uneven wall where a bookshelf may have been previously, on the right there is a homogenous wall.

![Figure 4-2: Floor plans with positions of Point U-value measurements](image)

Heat flux plates were placed at the horizontal centre of each wall, vertically they were placed one third and two thirds of the total floor to ceiling height. The heat flux plates were bonded to the wall using heat flux paste and the wires were fixed into the wall using wire clips. The thermocouples were placed two centimetres away from the heat flux plates, one centimetre off of the wall, this wire was also affixed using wire clips. The external thermocouples were positioned to match their internal counterparts. One water proof box was affixed to the wall for each pair of thermocouples to house the transmitter, as it was not weather resistant. The presence of solar gains can affect the results of the test, most of the equipment was in permanent shade,
however the west-southwest facing wall had direct afternoon sun upon it. To mitigate this effect, wooden shields were made and attached to the wall, to shade the sensors without effecting the measurements.

The measured heat flux, indoor and outdoor temperature data were combined to calculate point U-values of the walls of the two houses before and after internal wall insulation was applied. The British Standard ‘average method’ outlined in BS ISO 9869:2014 was used (BSI 2014) to analyse the data, Equation 26.

\[
U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{ij} - T_{ej})}
\]  

(Equation 26)

Where:

\( q_j \) is the heat flux

\( T_{ij} \) is the indoor air temperature 1cm from the wall’s surface

\( T_{ej} \) is the external air temperature 1cm from the wall’s surface

Figure 4-3: Thermal images showing inappropriate (left) and appropriate (right) locations to position heat flux sensors

The data were reviewed to ensure that the heat stored in the element did not change or that the element was not exposed to solar radiation during data collection. If either of these were the case the point U-values produced from the data would be incorrect. The British Standard provides a set of criteria for ensuring that the heat stored in the element did not vary over the course of the analysis, therefore deeming the data useable:
1. The analysis must be done on a period of time that is an integer multiple of 24 hours.
2. The analysis must be done on a minimum duration of 72 hours of data.
3. The final U-value produced by each analysis must be within +/- 5% of that 24 hours previously.
4. The U-value produced using the first 2/3 and last 2/3 of the data analysed must not deviate by more than 5%.

Through trial analysis of the data it became clear that contrary to usual data analysis, more data did not produce more accurate results: in order for the heat stored in the wall to stay constant the weather must also stay constant, if a long enough period of time passed the weather was likely to change. The data were therefore split into smaller time periods, analysed separately, then the U-values from each time period averaged to produce the final result. Usable data were found by analysing periods of data between 3 - 8 days long against the four criteria above for each trio of sensors: an outdoor temperature sensor, an indoor temperature sensor and a heat flux plate. More periods of valid data were found when there was a large difference between internal and external temperature and during periods of very stable external weather. There were more periods of valid data identified for some trios of sensors than for others; this is could be due to their location if they were more exposed to changing weather.

Figure 4.4: Experimental setup of U-value measurement, inside the house (left) and outside the house (right)
4.2.3 Co-heating

A method for performing co-heating tests was followed as developed by researchers at Leeds Beckett University, described in the “Whole House Heat Loss Test Method (Coheating)” (Johnston et al. 2013). The indoor temperature was kept elevated using fan heaters controlled with thermostats. Fans were used to mix the air, preventing air stratification. Whole house electricity consumption, individual room energy consumption, indoor air temperature and external air temperatures were recorded using other equipment detailed in this section 3.8. The equipment can be seen in Figure 4-5.

![Experimental setup of co-heating test](image)

**Figure 4-5: Experimental setup of co-heating test**

The houses were kept at an elevated indoor temperature for two weeks. A minimum difference between internal and external temperature of 10°C is desirable, which is easier to achieve in colder months. In the first test an indoor temperature of 25°C was used, the second test was done in May therefore the temperature was increased to 30°C to achieve the required delta T. Internal steady state conditions were needed therefore the houses were pre-heated for one week prior to the start of the tests to thoroughly heat the mass of the building. At the start of each test the following was done to minimise heat losses not associated with the fabric and minimise gains not produced by the electric fan heaters:

- Trickle vents and chimneys were sealed
- External windows and doors closed
• Windows were uncovered
• The central heating systems were turned off
• Sources of excess electrical gains were turned off
• Internal doors were wedged open
• U-bends in sinks and toilets were filled with water

Thermistors were placed in the centre of each room 0.85m off of the ground alongside the thermostat. The thermostat was plugged into a control box, which controlled the fan heater. The fan ran continuously to ensure even mixing of the air in the room. All items were plugged into an extension lead that in turn was plugged into an electricity consumption logger allowing the amount of electricity consumed in each room to be analysed. One set of equipment was used in each room, in a house with lower heat loss fewer heaters and fans can be used. The equipment was carefully positioned so that the air was heated evenly, but the fan heater did not heat the thermistor or thermostat directly. A humidity sensor was also placed in each house to ensure that the house was properly dried out. If the houses were too damp, some of the energy input to the house could have been used to evaporate moisture instead of increasing the temperature (Johnston et al. 2013).

The method of data analysis is important for reducing uncertainty and producing accurate heat transfer coefficients (HTCs). The uncertainties of the measuring equipment and a lack of knowledge of the boundary conditions for all surfaces of the houses are present regardless of data analysis method. In these tests the two semi-detached houses were heated to the same temperature, therefore removing the uncertainty involved with adjoined houses in co-heating tests i.e. that the neighbouring house is heated to an unknown temperature. The unknown boundary temperatures were those of the floors and the loft space, as these were not measured.

The ‘Basic Method’ of co-heating data analysis is done by performing regression between the daily heat input and the difference in internal and external temperature; the gradient of the line of best fit when forced through the origin of this graph is the HTC. Using the Basic Method introduces extra uncertainty to that described above because weather conditions are not fully incorporated. Similar to the U-value data analysis, the co-heating data analysis relies upon steady state conditions throughout the tests. In reality the house experienced dynamic conditions of weather, therefore it cannot be fully accurate. Some of this dynamism is diurnal and the Basic Method accounts for this by averaging the data into 24 hour periods. However a significant change in external conditions between one day and the next changes the amount of heat stored in the walls. This can result in time lags in the data and inaccurate results where heat is stored in the wall instead of passing through it. The elevated temperature used in testing minimises this effect, so that the change in the amount of heat storage is very small compared to that passing through it. Solar irradiation falling directly on the surface of the walls can significantly elevate wall temperature and increase the amount of energy stored. It is therefore important when dividing the data into discrete 24 hours periods that the weather and its effect on the fabric are in one period together. Therefore the data were divided into time periods starting at 04.00am,
ending at 03.55 the next calendar day. 04.00am is before sunrise at all times of the year so the effect of the sun on the fabric from the previous day will have largely dissipated by this time.

Heat losses and gains from the houses were affected by many weather variables: air temperature, solar irradiance, cloud cover, wind speed, humidity and precipitation. However the Basic model of heat in = heat out only includes air temperature. In order to take account for solar gains the ‘Siviour Plus Multiple Regression Method’ has been used as detailed by Jack (Jack 2015) and is used widely by many other experimenters (Butler & Dengel 2013). This method makes an allowance for solar gains and for radiative heat losses at night to the sky, however there are no tested methods to take account of exacerbated losses from wind speed, humidity or precipitation. To use the Siviour Plus Multiple Regression Method regression must be performed between the input heating power and the horizontal solar irradiance both divided by the difference between internal and external temperature. The gradient of the best of fit line is the ‘solar aperture’: the total radiative heat gains from the sun and radiative losses to the night sky through all surfaces in all directions modelled as a single South facing vertical window. This solar aperture is multiplied by the mean global solar radiation on each day to calculate the amount of power gained or lost. This power is then added to the electrical heating power used in the houses and plotted against ΔT. The gradient of the line of best fit is the heat transfer coefficient.

4.2.4 Thermography

An infrared camera survey was conducted to qualitatively assess where inconsistencies were present in the buildings’ fabric and have been used to assist in the explanation of why the buildings do not match reference values or calculated values.

It was necessary to do the surveys while there was a significant temperature difference between the internal and external environments and minimal temperature and pressure differences across the building (BSI 1999). This is why they were performed early in the morning in winter, before the sun had risen, to ensure that solar gains from the previous day had dissipated (Pearson 2002). The heating was on to offer a consistent and elevated indoor temperature. Weather forecasts were studied in advance to choose appropriate outdoor conditions. Both of the days had low wind speed, to minimise uneven building pressure, no precipitation and all building surfaces were dry, as a wetted surface effects heat transfer. A cloud covered sky was also chosen for the tests as the cold night sky would significantly increase radiant heat loss from areas of the building that had a good view of it.

A infrared camera: a FLIR T series (FLIR 2017) was used to produce the thermal images. Wide shots of the whole building were taken on each façade, as well as close up pictures of more interesting features. Typically a survey is done both internally and externally (Snell & Spring 2008), which was done here. Pearson describes thermography surveys as a three step program which was followed (Pearson 2002). Firstly it was necessary to be familiar with the building and its construction, so images can be understood. Secondly there must be suitable environmental conditions, as described above and thirdly a record kept of conditions of the day and the results.
4.3 Air permeability

4.3.1 Measured air permeability

The results from the test with all vents sealed: the measured infiltration and the results from the test with all vents open: total air permeability, which is the combined infiltration and ventilation, are presented in Table 4-1. Q50 is the measure of infiltration and air permeability from the pressurisation test, this is the volume of air leaving a house per hour, per m² of floor area at an elevated pressure of 50 Pa. The tests were done in both houses while they were uninsulated, and in the left house with IWI and after the removal of IWI. Permeability Test 1 was done on the 7th March 2015, with both houses in their uninsulated configuration. Permeability Test 2 was done on the 1st May 2015; the left house only was measured in its internally insulated state, to ascertain whether the installation of IWI might affect the air permeability. Permeability Test 3 was done on both houses on the 9th October 2015, once the internal wall insulation had been removed, to ascertain whether the IWI removal might affect air permeability.

The measured infiltrations and air permeabilities may be a slight overestimation due to the presence of a party wall between the houses. One house was depressurised at a time, so air will be forced through the party wall from the adjoining house. In normal operation little air would escape through the party wall as both houses would be at a similar pressure and very little heat would be lost as the house on the other side is likely to be at the same temperature and therefore the wall is considered adiabatic. Although this slight overestimation exists, this would be experienced when testing any adjoined dwelling.

<table>
<thead>
<tr>
<th>Insulation state</th>
<th>House</th>
<th>Test</th>
<th>Measured infiltration Q50 (m³/h.m²)</th>
<th>Measured air permeability: infiltration and ventilation Q50 (m³/h.m²)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Left</td>
<td>Test 1</td>
<td>8.02 ± 0.43</td>
<td>10.08 ± 0.36</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>Test 1</td>
<td>7.31 ± 0.41</td>
<td>9.53 ± 0.50</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>Test 3</td>
<td>7.49 ± 0.49</td>
<td>9.07 ± 0.48</td>
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<tr>
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<td>Right</td>
<td>Average</td>
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<td>9.29 ± 0.36</td>
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<tr>
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<td>Test 2</td>
<td>8.51 ± 0.45</td>
<td>9.89 ± 0.52</td>
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<tr>
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<td>Right</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Post insulation</td>
<td>Left</td>
<td>Test 3</td>
<td>8.39 ± 0.44</td>
<td>10.83 ± 0.58</td>
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<tr>
<td></td>
<td>Right</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: Uncertainties are calculated using the method detailed in Annex C of BS EN ISO 9972 (BSI 2015)

The houses perform better than the current limiting values in the Approved Documents for new buildings: a Q50 infiltration rate of 10 m³/h.m² (DCLG 2016a). This aligns with findings from previous studies (Birchall et al. 2011). The purposeful ventilation of the houses accounts for around 20% of the measured total air
permeability in the houses without insulation (Table 4-1). This was to be expected, there were significant gaps found across the building fabric. Figure 4-6 is a thermal image of a bay window, in the area circled there is noticeable air infiltration loss from an internal gap between the floor boards and the skirting board.

With no insulation the left and right house are matched for infiltration and air permeability (Table 4-1). The uncertainties of the fan depressurisation tests were calculated using the recommended method in Annex C of BS EN ISO 9972 (BSI 2015). This uncertainty calculated for each test shows that the houses can be considered to have the same air tightness as one another. The houses continue to have infiltrations and air permeabilities within the margin of error once the house has IWI installed, and once it is removed.

Figure 4-6: Thermal image of infiltration heat loss from the bay of the left house

It was hypothesised that the air permeability would increase in the left house once IWI was installed and once it was removed. This is because many holes were drilled into the inside surfaces of the external walls during IWI installation, these holes were an extra, although incomplete, air leakage path. Infiltration and air permeability appear to have increased marginally due to IWI (Table 4-1), however the increase is within the uncertainty margin.

4.3.2 Performance gap between measured and calculated air permeability

Infiltration and total air permeability were calculated in RdSAP using the construction details of the two houses. The models are provided in Appendix 1. They have been converted from air changes per hour to Q50, by multiplying figure by 20, the reverse of the method recommended when measured Q50 results are used in SAP.
These are presented in Table 4-2, with the difference from the calculated values. The total air permeability is different in the two houses when they are both uninsulated because the left house had an extra vent in the bathroom. Despite many of the same inputs, the left house with IWI installed is calculated to have higher total air permeability due to the reduction of floor area, because Q50 is air permeability per hour per m$^2$ of floor area.

There is a performance gap between the prediction and measurement of air permeability in the test houses. The predicted infiltration rates and total air permeabilities are up to 85% higher than measured values (Table 4-1). The calculation method in RdSAP overestimates both the infiltration and the ventilation air permeability of these solid wall houses.

### Table 4-2: Calculated air permeability

<table>
<thead>
<tr>
<th>Insulation state</th>
<th>House</th>
<th>Infiltration</th>
<th>Total air permeability: infiltration and ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Predicted Q50</td>
<td>Measured Q50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(m$^3$/h.m$^2$)</td>
<td>(m$^3$/h.m$^2$)</td>
</tr>
<tr>
<td>Uninsulated</td>
<td>Left</td>
<td>12.4 ± 0.43</td>
<td>8.02 ± 0.39</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>12.4 ± 0.28</td>
<td>7.40 ± 0.26</td>
</tr>
<tr>
<td>IWI</td>
<td>Left</td>
<td>12.4 ± 0.45</td>
<td>8.51 ± 0.41</td>
</tr>
</tbody>
</table>

Note: Uncertainties are calculated using the method detailed in Annex C of BS EN ISO 9972 (BSI 2015)

### 4.4 Thermal transmittance

#### 4.4.1 Measured thermal transmittances

The thermal transmittance of the two houses while in their uninsulated state was measured during the ‘Winter Matched Pair Test’: 14th February – 6th March 2015. Both houses were measured again, when the left house had IWI during the 'Winter Left House Insulated Test': 29th March – 1st May 2015.

The point U-values calculated from each valid data analysis period, and for each wall section are displayed in Table 4-3. The data periods have also been averaged into a mean point wall U-value for each wall section measured. An average of all wall sections has been taken to give a mean house average point U-value. The U-values are referred to as point U-values because each point U-value is only valid for the area of wall under the heat flux plate; they are not necessarily representative of the whole of the wall, particularly at wall junctions where there are thermal bridges (Figure 4-7). In the right house the house average does not include the values for the pantries, as these walls were not plastered. The house average U-value for a wall without plaster, measured in the pantries, is 1.95 W/m$^2$K.

The houses’ walls were thermally matched. The house average point U-value for the left house was 1.72 ±0.48 W/m$^2$K, it was almost the same in the right house at 1.73 ±0.48 W/m$^2$K (Table 4-3). This aligns with other UK studies of measured U-values of solid walls (Table 2-2). The internal wall insulation significantly reduced the
point U-values to 0.21 ±0.06 W/m²K. This is a dramatic reduction of point U-value in the left house of 88%. This aligns with previous research by Stevens and Bradford (2013), where a reduction in U-value of 89% was achieved using IWI in a solid brick wall house.

Table 4-3: Measured point U-values

<table>
<thead>
<tr>
<th>Insulation state</th>
<th>House</th>
<th>Data Analysis Period&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Point U-values (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Front Room</td>
<td>Dining Room</td>
</tr>
<tr>
<td></td>
<td></td>
<td>upper</td>
<td>lower</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data Period 1</td>
<td>1.59 ± 0.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 1</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 2</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 3</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 4</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 5</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 6</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 7</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean of</td>
<td>1.69 ± 0.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>periods 1-7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data Period 1</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 2</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 3</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 4</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data period 5</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean of</td>
<td>0.18 ± 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>periods 1-5</td>
<td></td>
</tr>
</tbody>
</table>

Note: Uncertainties of U-values are the arithmetic sum of uncertainties, ±28%, from BS ISO 9869:2014 (BSI 2014)

<sup>a</sup>Heat fluxes and temperatures were measured during the ‘Winter Matched Pair Test’ and the ‘Winter Left House Insulated Test’. There were fewer valid data periods found within the data during the ‘Winter Matched Pair Test’, so only one valid data period for the left house while uninsulated.

<sup>b</sup>Average does not include point U-values from pantries.

There were some minor equipment failures, which did not affect the results. Three external temperature sensors failed during testing: right house pantry upper; left house living room upper and left house living room lower. All of the external temperature data were reviewed and it was found that those temperature sensors placed on the same section of wall recorded temperatures within 0.2 °C of one another. Therefore the missing
external temperature data for the right house pantry upper were replaced with the set of data for the right house pantry lower. It was also found by looking at the opposite house that temperatures recorded by the external living room wall were within 0.7 °C of those recorded by the external dining room wall. Therefore the two missing sets of external temperature data for the living room in the left house were replaced by those from the dining room in the left house.

![Figure 4-7: Thermal images detailing thermal bridging on test houses](image)

Uncertainty in the calculation of point U-values from measured data arises from many sources. These include the accuracy of the temperature sensors, the heat flux plates and the data logger; the quality of the thermal contact achieved between the heat flux plate and the wall; the effect the heat flux plate has upon the localised heat flow; the effect of changing temperature increasing or decreasing the heat stored within the wall; and the temperature sensors not truly measuring air temperature, but a hybrid of air and radiant temperature. The total uncertainty in the method stated in BS ISO 9869:2014 is between the quadrature sum of uncertainties: ±14% and the arithmetic sum of uncertainties: ±28% (BSI 2014). Here the arithmetic sum of 28% will be used as the uncertainty in the point U-values. Further uncertainty could arise by assuming that the point U-values measured are representative of the entire of the external walls. The uncertainty of the house mean is an expanded combined uncertainty calculated through summation in quadrature.

There was variation in the point U-values both between different sections of wall and between data periods for the same wall, although these are not significant when considering the ±28% uncertainty. This variation is partly due to the uncertainty in the test procedure, but also partly a reflection of the genuine variation that occurs in wall U-values. A pattern can be seen in the right uninsulated and the left insulated results, whereby sensors placed in the upper position on the wall have slightly lower U-values than those placed lower. This is due to natural variation in the wall, whereby the lower parts of the wall will hold more moisture as it is drawn up from the ground, increasing thermal conductivity. This can be seen in Figure 4-8, where the temperature is warmer at the bottom of the wall than top, indicating that the heat loss is greater. The variation across the different sections of walls could also be due to greater or smaller water content and also construction differences where plaster is thicker on some sections of wall. The variation seen in point U-values of the same
section of wall produced by different periods of data could be due to a minor change in point U-value through time or due to the uncertainty of the measurements and associated calculations.

Figure 4-8: Thermal image of side-wall heat loss decreasing as the distance from the ground increases

4.4.2 Performance gap between measured and calculated thermal transmittance

To estimate the thermal conductivity of the bricks when calculating U-values, the densities of nine bricks from the houses were measured in accordance with the methods in BS EN 772-13: 2001 (2001a) and BS EN 772-3:1998 (1998); the average net dry density of the brick was 1800 kg/m³. CIBSE Guide A (CIBSE 2015a) has a reference table of thermal conductivities: the thermal conductivity of an exposed brick with a density of 1800 kg/m³ and is unprotected from the weather is 0.83 W/mK.

Thermal transmittances were calculated using BS EN ISO 6946:2007, as described in section 3.8.2. The calculated thermal transmittance of the solid brick walls of these houses at a thickness of 242mm (Table 3-1: Brick wall thicknesses) is 1.94 W/m²K (Table 4.4). This U-value is lower than the 2.1 W/m²K recommended for use in RdSAP, this is due to the longer than average bricks resulting in a thicker wall.
Table 4-4: Calculation of the thermal resistance of a solid brick wall

<table>
<thead>
<tr>
<th>Layer</th>
<th>d (mm)</th>
<th>( \lambda ) (W/mK)</th>
<th>( R ) (m²K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{se} )</td>
<td>-</td>
<td>-</td>
<td>0.040</td>
</tr>
<tr>
<td>Brick</td>
<td>110</td>
<td>0.83</td>
<td>0.133</td>
</tr>
<tr>
<td>Mortar</td>
<td>9</td>
<td>0.94</td>
<td>0.010</td>
</tr>
<tr>
<td>Brick</td>
<td>110</td>
<td>0.83</td>
<td>0.133</td>
</tr>
<tr>
<td>Plaster</td>
<td>13</td>
<td>0.18</td>
<td>0.072</td>
</tr>
<tr>
<td>( R_{si} )</td>
<td>-</td>
<td>-</td>
<td>0.130</td>
</tr>
<tr>
<td><strong>Total R</strong></td>
<td></td>
<td></td>
<td><strong>0.517</strong></td>
</tr>
</tbody>
</table>

\[ U = 1.94 \text{ W/m}^2\text{K} \]

Solid brick walls are in fact not solid (Li et al. 2014). Walls were traditionally made without a full cavity by laying header bricks (the smallest face of a brick laid with its longest side horizontally) and stretcher bricks (the middle sized face of a brick laid with its longest side horizontally) in various inter-locking patterns. For the bricks used in these houses, the width of two stretcher laid one behind the other is 9mm shorter than a header brick, therefore a space is left between stretcher bricks when they are laid. These stretcher bricks did not have mortar put between them, resulting in a micro-cavity between stretcher in solid brick walls. A picture of the micro-cavities found in these test houses can be seen in Figure 4-9. A micro-cavity will decrease the expected U-value of a wall, because an air gap is less thermally conductive than brick or mortar. The bond pattern used to construct a wall will determine the number of header bricks that bridge the micro-cavity and therefore the overall heat loss from the wall is dependent upon the brick bond.

**Figure 4-9: View of micro-cavities within solid brick walls in the bay window of the right house**

The brick bond used to construct these houses was a Monk bond, whereby two stretcher are laid then one header in a continuous pattern, Figure 4-10. Although this is the general pattern it can be seen from Figure 4-10 that the pattern is not always regular, resulting in more headers or stretchers in some places.

Based upon a typical Monk bond the percentage of the wall made from stretchers is 81% and of headers is 19%. Therefore 81% of the wall has a micro-cavity.
The calculated thermal transmittance of the solid brick walls of the house constructed using a Monk bond with micro-cavities is 1.70 W/m²K (Table 4.5). These compare well to the average measured wall U-values of 1.73 W/m²K (Table 4-3); if the construction of the wall is known it is possible to accurately calculate wall U-value. There will be variation across the wall, where there is a header the U-value is 1.93 W/m²K, where there are two stretchers with a micro-cavity in between the U-value is 1.52 W/m²K. The wall averaged calculated U-value of 1.70 W/m²K is significantly lower than the calculated value for this wall without micro-cavities of 1.94 W/m²K, the micro-cavities are important to overall thermal performance. The micro-cavity calculated U-values of 1.70 W/m²K and the measured U-values of 1.73 W/m²K are significantly lower than the standard RdSAP value of 2.1 W/m²K. A performance gap is present if this incorrect value is used in building energy calculations for these buildings.

The same method was used to calculate the U-value of the solid brick walls with micro-cavities, insulated with 50mm of PIR insulation laminated at the front with 12.5mm of plasterboard, on a metal frame system at 600m centres. Very little of the metal frame system touched the external walls, limiting thermal bridging. There was an air gap of at least 25mm in width between the wall and the insulation which was backed with foil. This reduced the radiative heat loss across the air gap behind the insulation; therefore the air gap had a thermal resistance of 0.44 m²K/W (CIBSE 2015a). Corrections were added to the U-value due to the presence of metal fasteners $U_f$ and small air gaps between the insulation boards $U_g$, this is detailed in BS EN ISO 6946 (2007c).
Table 4-5: Calculation of the thermal resistance of a solid brick wall with micro-cavities.

<table>
<thead>
<tr>
<th>Layer</th>
<th>d (mm)</th>
<th>λ (W/mK)</th>
<th>R (m²K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rse</td>
<td>-</td>
<td>-</td>
<td>0.040</td>
</tr>
<tr>
<td>Stretcher brick</td>
<td>110</td>
<td>0.83</td>
<td>0.133</td>
</tr>
<tr>
<td>Micro-cavity</td>
<td>9</td>
<td>0.150</td>
<td>0.150</td>
</tr>
<tr>
<td>Header brick</td>
<td>229</td>
<td>0.83</td>
<td>0.276</td>
</tr>
<tr>
<td>Plaster</td>
<td>13</td>
<td>0.18</td>
<td>0.072</td>
</tr>
<tr>
<td>Rsi</td>
<td>-</td>
<td>-</td>
<td>0.130</td>
</tr>
<tr>
<td>Rl</td>
<td></td>
<td></td>
<td>0.550</td>
</tr>
<tr>
<td>Ru</td>
<td></td>
<td></td>
<td>0.625</td>
</tr>
<tr>
<td>Rb</td>
<td></td>
<td></td>
<td>0.588</td>
</tr>
<tr>
<td>U</td>
<td></td>
<td></td>
<td>1.70 W/m²K</td>
</tr>
</tbody>
</table>

The solid walls with IWI installed were calculated to have a U-value of 0.30 W/m²K (Table 4-6); this is significantly lower than the RdSAP tabulated value of 0.6 W/m²K. However, it is higher than the measured U-values of 0.21 ±0.04 W/m²K (Table 4-3). To calculate a U-value of 0.21 ±0.04 W/m²K, a basic sensitivity analysis was done, changing the thermal resistances of each component of the U-value calculation to match the measured and calculated values. The calculated U-value of the uninsulated wall aligned with that which was measured, as demonstrated above, and was therefore not altered in the sensitivity analysis. The discrepancy between the measured and calculated U-value of the wall with IWI was therefore either due to the insulation board, the air gap or the fixings. The values match when all three are considered:

- The thermal resistance of the PIR insulation boards is likely to be well defined by the insulation manufacturer; however there may have been some minor variation in their manufacture that meant a marginally lower U-value. An increase in insulation thickness by 1mm and the λ by 0.001 W/mK reduces the U-value to 0.287 W/m²K.
- The assumed resistance of the air gap could be increased marginally by 0.1 m²K/W, reducing the U-value to 0.280 W/m²K.
- The correction for metal fasteners and air gaps (Uf and Ug) between boards could be assumed to be too large; removing them reduces the calculated U-value by a further to 0.256 W/m²K.

These factors together could account for the discrepancy between measured and calculated value. Considering the measurement uncertainty was ±0.04 W/m²K, the measured value could be as high as 0.25 W/m²K. As seen in the bullet points above the calculated value could be reduced to 0.256 W/m²K; leaving very little difference.
Table 4-6: Calculation of the thermal resistance of a solid brick wall with 50mm of internal wall insulation applied

<table>
<thead>
<tr>
<th>Layer</th>
<th>d (mm)</th>
<th>λ (W/mK)</th>
<th>R (m²K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rse</td>
<td></td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Stretcher brick</td>
<td>110</td>
<td>0.83</td>
<td>0.1325</td>
</tr>
<tr>
<td>Micro-cavity</td>
<td>9</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Header Brick</td>
<td>229</td>
<td>0.83</td>
<td>0.2759</td>
</tr>
<tr>
<td>Plaster</td>
<td>13</td>
<td>0.18</td>
<td>0.0722</td>
</tr>
<tr>
<td>Air gap</td>
<td>&gt;25</td>
<td>-</td>
<td>0.44</td>
</tr>
<tr>
<td>Metal frame</td>
<td>&gt;25</td>
<td></td>
<td>0.0005</td>
</tr>
<tr>
<td>IWI</td>
<td>50</td>
<td>0.02</td>
<td>2.5</td>
</tr>
<tr>
<td>plasterboard</td>
<td>12.5</td>
<td>0.19</td>
<td>0.0658</td>
</tr>
<tr>
<td>Rsi</td>
<td></td>
<td></td>
<td>0.013</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
R_L &= 3.611 \\
R_U &= 3.634 \\
R_b &= 3.623
\end{align*}
\]

\[
U_f = 0.02 \text{ W/m}^2\text{K} \\
U_k = 0.01 \text{ W/m}^2\text{K} \\
U = 0.30 \text{ W/m}^2\text{K}
\]

It is also important to note that BS EN ISO 6946:2007 calculates U-values considering one dimensional heat flow. This is a simplification of reality that allows calculations to be done easily without the use of computer modelling software. This simplification produced a very accurate prediction of the U-value of the solid, single mass of wall. However, due to the presence of the air gap the theory of one-dimensional heat flow may be an over-simplification, leading to inaccurate predictions.

The BS EN ISO 6946:2007 calculation method and guidance did not produce correct predictions of the wall U-value when IWI was installed. This finding is anomalous with one prior study in the field that compared measured and calculated U-values of 4 solid walls with insulated plaster boards installed; in the study their measurements and calculations matched well (Rhee-Duverne & Baker 2013). The differences between this work and that study are the installation method, in this study a metal frame system was used requiring the addition of the calculation of the air gap and the correction factors. The U-value of this system was not accurately calculated in this study using the current guidance, the method may need improvement.
4.5 Whole house heat transfer coefficient

4.5.1 Measured whole house heat transfer coefficient

Co-heating test 1 was done between the 20th January 2015 and the 1st February 2015, when both houses were uninsulated. Co-heating test 2 was done between the 6th and the 19th May 2015, when the left house had IWI installed. The co-heating tests and the analysis methods are described fully above in Section 0. Three different analysis methods were trialled to analyse the data: no solar correction, multiple regression and siviour plus regression; these methods are compared in Figure 4-11. The purpose of the multiple regression analysis and the siviour plus analysis is to take account of solar gains, the effectiveness of these methods can be assessed by how well the regression lines fit the data, the $R^2$ value. In both houses in co-heating test 1 and the right house in co-heating test 2 the siviour plus regression method provided the best analysis of the data. In co-heating test 2 in the left house the data was best analysed by including no solar analysis. To compare the houses and test periods against one another the same analysis method was used for all tests: the siviour plus regression method. Ultimately, the heat transfer coefficients produced by the three methods for each test and house are very similar; the largest difference of 15 W/K between analysis methods was produced in Test 2 in the left house with IWI. The results of the final co-heating analysis using siviour plus regression analysis are presented in Figure 4-12 and Table 4-7.

The left and right uninsulated houses were thermally matched (Figure 4-12, Table 4-7). The total uncertainty of the HTC from a co-heating test and Siviour Plus Regression analysis is ±10% (Jack et al. 2017), HTCs within this band of uncertainty can be considered the same. The HTC of the left house was 238 W/K, 2% higher than the right house which was 233 W/K (the HTC of the right house is an average of the results from Co-heating Test 1: 240 W/K and Co-heating Test 2: 225 W/K). Applying internal wall insulation reduced total house heat loss by 39%. The left house with internal wall insulation had a total measured HTC of 144 W/K, reduced from 238 W/K (Table 4-7). The uncertainties in the measurements have been combined using summation in quadrature and are less than one third of the reduction in HTC.
Figure 4-11: Comparison of data analysis methods for the co-heating test data
Table 4-7: Measured heat transfer coefficients

<table>
<thead>
<tr>
<th>Insulation state</th>
<th>House</th>
<th>Measured HTC of fabric and infiltration (W/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uninsulated</td>
<td>Left</td>
<td>238 ±24</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>233 ±23</td>
</tr>
<tr>
<td>IWI</td>
<td>Left</td>
<td>144 ±14</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-</td>
</tr>
</tbody>
</table>

| Reduction in HTC of left house | 94 ±28 (39%) |

*Note: uncertainty of HTC is ±10% (Jack 2015)*

In Co-heating Test 1, when both houses were uninsulated, a difference between the outdoor and indoor temperatures (ΔT) of 15 °C was achieved throughout, with indoor temperatures set at 25 °C (Figure 4-13). In Co-heating Test 2, when the left house was insulated, the indoor temperature was set to 30 °C to achieve the minimum ΔT of 10 °C. There was not a ΔT of 10 °C at all times through each day, however the average ΔT on all days was more than 10 °C. The indoor temperatures were very stable; the mean air temperature in Co-heating Test 1 in the left house was 25.2 °C, Standard Deviation (sd) = 0.3, in the right house it was 24.9 °C, sd =0.1. The mean temperature in Co-heating Test 2 in the left house was 30.1 °C, sd = 0.1, in the right house it was 30.2 °C, sd = 0.1.
Figure 4-12: Co-heating analysis of Test 1 and 2 using siviour plus regression analysis
During Co-heating Test 2 there were significantly higher external temperatures and more solar irradiance compared to Co-heating Test 1 (Figure 4-13). The mean percentage of heat power due to radiative gains (+) or losses (-) during Co-heating Test 1 for the left house was -2.7%, the right house was +4.1%; during Co-heating Test 2 for the left house was +11%, the right house was +3.5%. Comparing the right house, which remained uninsulated for Co-heating Test 1 and 2, the percentage of heating power from solar stayed very similar. This was not to be expected as solar was larger and the external temperature was also higher. This may be highlighting inaccuracy in the analysis. The left, insulated house, in Co-heating Test 2 was heated by a larger proportion by the sun than in Co-heating Test 1 when it was uninsulated; this was to be expected as it required less heating power due to the presence of insulation and the higher external temperatures.

![Graphs showing indoor, external temperatures, and solar radiation for Co-heating Tests 1 and 2](image)

**Figure 4-13: Indoor temperatures, external temperatures and solar radiation in co-heating tests 1 and 2**

Wind and precipitation during the tests were studied, to identify when the houses were subject to excess heat transfer from these weather conditions, Figure 4-14. More than a ‘gentle breeze’, according to the Beaufort scale, is above 5m/s (The Met Office 2015); this was chosen as a nominally significant amount of wind. The days with rainfall or high winds were identified in the graphs of total power vs temperature difference. They
did not produce outliers within the regression, implying they did not increase heat transfer significantly enough to warrant exclusion or further investigation.

![Wind and Rainfall Graphs](image)

**Figure 4-14:** Wind speed and rainfall during co-heating tests

### 4.5.2 Performance gap between measured and calculated whole house heat transfer coefficient

‘Typical RdSAP’ models were used to calculate the houses’ HTCs, this method used standard assumptions (Table 4-8). The heat transfer coefficients of the left and right uninsulated houses calculated using the typical RdSAP models are almost identical (Table 4-8) at 360 and 358 W/K respectively. The introduction of internal wall insulation into this typical RdSAP model reduces the HTC by 44% to 201 W/K.

‘Improved RdSAP’ models were also used to calculate the houses HTCs (Table 4-8), this method incorporated measured wall U-values and air permeability values (section 3.8.1). The air permeabilities (4.3.1) and U-values (4.4.1) measured in the houses were lower than the typical RdSAP calculated values and the standard
assumptions. By including these measured data into the improved RdSAP models it reduced the uninsulated and insulated HTCs significantly compared to the typical RdSAP models. The internal wall insulation reduced the improved RdSAP modelled HTC of the left house by 52%

Table 4-8: Measured and calculated whole house heat transfer coefficients

<table>
<thead>
<tr>
<th>Insulation state</th>
<th>House</th>
<th>Measured Co-heating Test</th>
<th>Typical RdSAP model</th>
<th>Improved RdSAP model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HTC (W/K)</td>
<td>HTC (W/K)</td>
<td>Over-prediction (%)</td>
</tr>
<tr>
<td>Uninsulated</td>
<td>Left</td>
<td>245 ±25</td>
<td>360</td>
<td>47%</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>240 ±24</td>
<td>358</td>
<td>49%</td>
</tr>
<tr>
<td>Internally Insulated</td>
<td>Left</td>
<td>149 ±15</td>
<td>201</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reduction in left house</td>
<td>96 ±40 (39%)</td>
<td>159 (44%)</td>
<td>4%</td>
<td></td>
</tr>
</tbody>
</table>

Note: uncertainty of measured HTC is ±10% (Jack 2015)

Ventilation in the houses was sealed during the co-heating tests, so the measured HTCs were of the fabric and infiltration only. To produce a total measured HTC that could be compared against calculated values from RdSAP, ventilation heat loss was calculated from measured ventilation rates (Table 4-1) using RdSAP as a tool and added to the measured heat transfer coefficient (Table 4-7).

The ‘Typical RdSAP’ models overestimated the HTCs of the left house by 47% and the right house by 49% (Table 4-8); it also overestimated the HTC of the left house with IWI installed by 35%. These results align with other’s research into the performance gap of buildings (section 1.1.4).

The ‘Improved RdSAP’ models predicted the HTCs of the houses better than the ‘Typical RdSAP’ model. The ‘Improved RdSAP’ predictions of the uninsulated house were still inaccurate (Table 4-8), however it predicted the HTC of the internally insulated house very accurately (Table 4-8). The inaccuracy in the predictions of the HTCs of the uninsulated houses could be due to standard assumptions of the U-values of elements other than the walls of the building, such as the floor and the roof. However, if this was the case, this inaccuracy should still be present when calculating the HTC of the insulated house. Another possibility is that inaccuracy comes from accounting for thermal bridges, which are included in RdSAP by multiplying the internal surface area of the building by 0.15, then adding this to the fabric and ventilation HTCs to produce the total calculated HTC. Although U-values were measured and inputted into the RdSAP model, these were point U-values, the true effect of bridging was unknown. It is possible that the RdSAP method of accounting for bridges works well when considering the internally insulated walls, which were bridged heavily by internal walls penetrating to the outside walls. However, it may have severely overestimated the bridges in the uninsulated houses.
Inaccurate predictions are a problem, because RdSAP is used when deciding to insulate buildings and to calculate payback periods. Although an excellent saving in energy was made, it was predicted to be much larger. This difference means less energy than expected would be saved; this performance gap is caused by not accurately calculating the original building performance.

4.6 Chapter Summary

The houses’ thermal performance demonstrated that they are a matched pair. Their air permeabilities, U-values and HTCs without insulation are very similar, and would be considered the same within the margins of error. The measured infiltration in the uninsulated left house was 8.02 m³/h.m² and in the right house was 7.40 m³/h.m²; these are better than the current limiting values in the Building Regulations. The measured point U-values for the walls when uninsulated were 1.73 W/m²K in the left house and 1.73 W/m²K in the right house, similar to that calculated at 1.7 W/m²K; significantly lower than the values assumed in RdSAP of 2.1 W/m²K. The measured heat transfer coefficients for the uninsulated houses were 245 W/K for the left house and 240 W/K for the right house.

Internal wall insulation had no effect on the measured infiltration before IWI: 8.02 m³/h.m², during IWI: 8.51 m³/h.m² and after the IWI was removed: 8.39 ach⁻¹. The measured point U-values of the internally insulated walls were 0.21 W/m²K which is a significant reduction from 1.73 W/m²K. The measured heat transfer coefficient for the left house once insulated was 149 W/K, a significant reduction of 39%.

RdSAP models were produced of the houses both with and without internal wall insulation to predict air permeabilities and whole house heat transfer coefficients. BS EN ISO 6946:2007 (2007c) was used to calculate U-values. RdSAP over-predicted air permeabilities by up to 85%. The ISO method could accurately predict U-values with the identification of a solid wall micro-cavity. The Typical RdSAP models over-predicted the HTC for the uninsulated houses by up to 49%, and the house with IWI by 35%. Measured air permeabilities and U-values were used as inputs to produce an Improved RdSAP model. The Improved RdSAP model predicted the uninsulated houses’ HTCs better than the Typical RdSAP model, but still poorly, however predicted the HTC of the house with IWI accurately.
5 The impact of IWI on energy demand

5.1 Introduction

The purpose of this chapter is to answer the research question: how much energy is saved by installing internal wall insulation in a solid wall house? This is in fulfilment of Objective 4. Energy demand and temperature data were collected in the test houses during the winter of 2015. Two winter monitoring tests were completed, Winter Test 1: Matched Pair Test, when both houses were in their uninsulated, original state; and Winter Test 2: Left House Insulated Test, when the left house had internal wall insulation. Details of the tests and the methods are given in section 3.5. A side-by-side comparison of the two houses was used to compare the energy demand data in each test period (section 5.2). The energy savings were then extrapolated to a standard Test Reference Year using linear regression models (section 5.3). This annual heat demand was compared to RdSAP modelled energy demand in the left house, and to identify any performance gap (section 5.4).

5.2 Assessing energy savings using a side-by-side comparison of two houses

A direct side-by-side comparison, fully detailed in section 3.7.1, has been used to compare the two houses during each test period (Figure 5-1, Figure 5-2, Table 5-1). Data collected from the two houses during Winter Test 1: Matched Pair Test (Figure 5-1) were compared to assess the similarity in energy demand between the houses when neither had any insulation. Data collected during the Winter Test 2: Left House Insulated Test (Figure 5-2) were compared to assess how much lower the energy demand of the insulated house was compared with its uninsulated neighbour. The energy demand of the houses cannot be directly compared across the two tests because the tests were of different lengths, and done under different weather conditions (Figure 5-1, Figure 5-2, Table 5-1); the next sections in this chapter normalise data to allow comparison across test periods and extrapolation into a year of data.

The measured central heating demand in each test, and the percentage difference between the houses, is displayed in Table 5-1. During Winter Test 1 the left house required 14% more heat from the central heating system; during Winter Test 2 the left house required 158% less heat from the central heating system. However, due to failure of the heat emitters of the synthetic occupancy equipment, slightly different amounts of heat were provided to each house from the synthetic occupancy equipment. Further to this the different orientations of the houses meant that the solar gains differed slightly. To correct for these effects the estimated total heat gains were calculated (Table 5-1). The estimated total heat gains were the sum of the measured central heating demand, the measured synthetic occupancy gains and the estimated solar gains. The solar gains were estimated from measured solar irradiance (section 3.9.3) using the SAP method (DECC 2013). The total heat losses were calculated from the mean indoor air temperature, mean external temperature and the heat transfer coefficient, further detailed in Chapter 3.
Figure 5-1: Winter Test 1 volumetrically weighted indoor air temperatures, heat consumption, outdoor air temperatures and solar radiation
Figure 5-2: Winter Test 2 volumetrically weighted indoor air temperatures, heat consumption, outdoor air temperatures and solar radiation
Table 5-1: Side-by-side comparison of winter energy demand

<table>
<thead>
<tr>
<th></th>
<th>Winter Test 1: Matched Pair Test</th>
<th>Winter Test 2: Left House Insulated Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17/02/2015 – 06/03/2015 n= 18 days</td>
<td>29/03/2015 – 01/05/2015 n = 33 days</td>
</tr>
<tr>
<td></td>
<td>Left House</td>
<td>Right House</td>
</tr>
<tr>
<td>----------------------</td>
<td>------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Measured central heating demand (kWh)</td>
<td>935</td>
<td>801</td>
</tr>
<tr>
<td>Measured synthetic occupancy gains (kWh)</td>
<td>211</td>
<td>219</td>
</tr>
<tr>
<td>Estimated solar gains (kWh)</td>
<td>109</td>
<td>105</td>
</tr>
<tr>
<td>Estimated total heat gains (kWh)</td>
<td>1255</td>
<td>1125</td>
</tr>
<tr>
<td>Measured mean indoor air temperature (°C)</td>
<td>17.5</td>
<td>17.4</td>
</tr>
<tr>
<td>Measured mean external air temperature (°C)</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Measured heat transfer coefficient (W/K)(^a)</td>
<td>245</td>
<td>240</td>
</tr>
<tr>
<td>Estimated total heat losses (kWh)(^b)</td>
<td>1259</td>
<td>1225</td>
</tr>
</tbody>
</table>

\(^a\) The heat transfer coefficient was calculated from measured data in section 4.5.1.

\(^b\) Calculated using (Equation 2).

During the Winter Test 1, when both houses were uninsulated, the estimated total heat gains of the left house were 10% higher than that of the right house (Table 5-1). This is due in part to the higher indoor air temperature in the left house. The left house was heated to a 0.1 °C higher indoor air temperature, resulting in a higher central heating demand, this was due to the inaccuracy of the heating system controls. This higher temperature caused a mismatch between the houses’ total heat gains. The higher indoor temperature and marginally higher heat transfer coefficient of the left house resulted in higher estimated heat losses and therefore more heat was required from the central heating system.

The energy demand of the two houses in Winter Test 1 was the same, considering the uncertainty of the measurements. The test facility was demonstrated in Chapter 4 to be a thermally matched pair of houses: the air permeability, wall U-values and the heat transfer coefficients of the uninsulated houses were very similar; it is therefore unlikely that the 10% difference in estimated total heat gains was a true difference between the houses. The difference was caused by a mismatch in indoor temperature, experimental uncertainty and uncertainty in the estimation of solar gains. This is further evidenced by the difference in the gains to and losses from each house in each test period (Table 5-1). The gains and losses should be the same for each house, to achieve a set temperature heat that is put into the house must have left (heat balance), and due to the long time period storage effects should be negligible; the difference in gains and losses, is due to the experimental uncertainty in the measurements and the averaging effects of the simple calculation methods used to estimate them.
In Winter Test 2: Left House Insulated Test, the left house had internal wall insulation applied. This test was used to test the reduction in building energy demand due to IWI. In this test the left house required 46% less estimated total heat gains than the right house, to achieve an average temperature one degree warmer. The set-point temperatures in the two houses were the same; the temperature in the left house was on average one degree warmer because the house with IWI cooled slower, this can be seen in Figure 5-3. Winter Test 2 was carried out between the 29/03/2015 and the 01/05/2015. In this period of the year the solar gains contributed 36% of the estimated total heat gains, resulting in 5 days where no central heating was required at all. At other times of the year when there is less solar irradiance the difference in measured central heating demand between the houses would be much lower: the left house required 158% less heat from the central heating system in this test at this time of year; this would not be representative of a year of energy saving.

![Cooling curves of five days of Winter Test 2: Left House Insulated](image)

**Figure 5-3: Cooling curves of five days of Winter Test 2: Left House Insulated**

These tests demonstrate that the houses were reasonably matched and that significant energy savings can be made through the installation of IWI. However, these results cannot be extrapolated directly to estimate the energy saving over a year. This is for two reasons, firstly some experimental uncertainty was observed and secondly the measurement periods were short, at different times of year and under different weather conditions. Models built using this measured data are therefore needed to estimate the annual energy savings due to IWI.

### 5.3 Extrapolating the measured data into annual energy savings

The measured energy demand data from the two winter energy demand tests were extrapolated to annual energy demand of a house with and without IWI. To extrapolate the data a suitable model was required. Both a degree-days model and a linear regression model were tested by data-splitting as described in section 3.7.7. The linear regression model predicted energy demand the most accurately and was therefore chosen to predict annual energy demand.
5.3.1 The degree-days method

The degree-days method is described in section 3.7.5. Two degree-day models were built on the energy demand data collected in the right houses, one from each test:

**D-D R1**: built using the data from the right house during Winter Test 1: Matched Pair Test

(D-D: Degree-days, R: Right, 1: Winter Test 1)

**D-D R2,** built using the data from the right house during Winter Test 2: Left House Insulated Test

(D-D: Degree-days, R: Right, 2: Winter Test 2)

Each model was then used to predict the energy demand of the other test period, demonstrating its ability to produce accurate predictions of energy demand in other time periods. If a model can predict energy demand from another time period accurately, it can predict annual energy accurately.

Both of the degree-day models predicted energy demand poorly. The degree-day model D-D R2, built using the data from the right house in Winter Test 2: Left House Insulated Test, under-predicted the central heating demand in the right house in Winter Test 1: Matched Pair Test by 21% (Table 5-2). The D-D R1 model, built using data from Winter Test 1, over-predicted the central heating demand in Winter Test 2 by 67% (Table 5-2).

Figure 5-4 shows the measured daily energy demand and the daily energy demand predicted using degree-day models. Model D-D R2 both over-predicts and under-predicts central heating demand on different days, whereas D-D R1 routinely over-predicts daily central heating demand. There were no correlations found between the accuracy of prediction and external temperature, solar gains, wind or rain. The average baseline temperatures for both test periods were calculated to be similar, despite significantly higher gains in the Winter Left House Insulated Test (Table 5-1, Figure 5-4). The number of degree-days calculated was higher for Winter Test 2 than Winter Test 1, whereas it should have been the opposite way round: the central heating demand was higher in the first test. This resulted in the incorrect prediction of central heating demand.

There are limitations to the degree-days method as the calculation assumes steady-state conditions in a dynamic system. Generally the method is used over long periods of time, months and years, allowing the baseline temperatures to be calculated using a whole year of data. An annual prediction would average the effect of the changing heat storage in the thermal mass. However here only short periods of data are available, which possibly means the method here is inappropriate for use.
Table 5-2: Predicted heat consumption using the degree-days method

<table>
<thead>
<tr>
<th></th>
<th>Winter Test 1: Matched Pair Test (17/02/2015 – 06/03/2015)</th>
<th>Winter Test 2: Left House Insulated Test (29/03/2015 – 01/05/2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model built on test data</td>
<td>D-D R1</td>
<td>D-D R2</td>
</tr>
<tr>
<td>Degree-Days (HDD)</td>
<td>158</td>
<td>173</td>
</tr>
<tr>
<td>Average Baseline Temperature (°C)</td>
<td>14.3</td>
<td>14.4</td>
</tr>
<tr>
<td>Measured Central Heating Demand (kWh)</td>
<td>801</td>
<td>616</td>
</tr>
<tr>
<td>Model used for prediction</td>
<td>D-D R2</td>
<td>D-D R1</td>
</tr>
<tr>
<td>Predicted Central Heating Demand (kWh)</td>
<td>632</td>
<td>1027</td>
</tr>
<tr>
<td>Difference between measured and predicted central heating demand (kWh)</td>
<td>-21%</td>
<td>67%</td>
</tr>
</tbody>
</table>

There is no clear reason why the degree-days model predicts poorly. Most of the inputs used to build the degree-days models were measured; each measured input comes with its own uncertainty which was then brought into the models, however these models will be undoubtedly more accurate than one built using assumed values. The method appears to have underestimated how the solar gains effect the heat demand, this could be those due to solar radiation on the opaque surfaces, however this is thought to be 1-2 orders of magnitude smaller than gains through the windows (Kreider 2010). These shortwave gains are ignored in most simple building energy models such as the SAP, as are the longwave radiation losses from wall surface, representing either would not make a large enough difference to improve the calculation. Although not seen in the model the losses may have also been underestimated, as only outdoor temperature and solar radiation were used as weather variables, wind and precipitation could have significant effects on the amount of energy used.

If degree-days models built on a daily scale and produced from measured data cannot predict central heating demand better, it is unlikely those used for building management with assumed values and built on a monthly scale are offering accurate predictions. Further work is required, with more split data sets to investigate the efficacy of the degree-days method.
5.3.2 The linear regression method

The theory of linear regression and the method used to produce the most accurate linear regression model from the measured data are described in section 3.7.6. Two linear regression models were built:

**MR R1**: built using the data from the right house during Winter Test 1: Matched Pair Test

(MR: Multiple Regression, R: Right, 1: Winter Test 1)

**MR R2**, built using the data from the right house during Winter Test 2: Left House Insulated Test

(MR: Multiple Regression, R: Right, 2: Winter Test 2)
The same data splitting and validation method was used for the linear regression models that was used for the degree-days models. Each model was used to predict the energy demand of the other test period. Accurate predictions of another time period validates their use for predicting annual total internal gains (section 3.7.7).

Different multiple regression models were produced and tested to predict different measures of heating demand from several different outdoor predictor variables. The full list of dependent and independent variables trialled and the process is given in section 3.7.5. The most accurate models for the right houses in both tests used total internal gains (central heating demand + gains from people and appliances) as the dependent variable and the exponentially weighted outdoor running mean temperature with an alpha of 0.55 ($T_{WO,0.55}$) and solar radiation as the independent variables, these are the models presented in Table 5-3.

The linear regression models predicted total internal gains accurately. The linear regression model MR R2, built using the data from the right house in Winter Test 2, under-predicted the total internal gains in the right house in Winter Test 1 by 1% (Table 5-3). The MR R1 model over-predicted the total internal gains in Winter Left House Insulated Test by 14% (Table 5-3). Models MR R1 and MR R2 conform to all of the assumptions of regression, detailed in Table 5-4.

**Table 5-3: Predicted heat consumption for the right house using multiple regression models**

<table>
<thead>
<tr>
<th>Model built on test data</th>
<th>Dependent variable, y</th>
<th>Independent variables</th>
<th>Model</th>
<th>$R^2$</th>
<th>Measured total internal gains (kWh)</th>
<th>Model used for prediction</th>
<th>Predicted total internal gains (kWh)</th>
<th>Difference between measured and predicted total internal gains (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Test 1: Matched Pair Test (17/02/2015 - 06/03/2015)</td>
<td>Total internal gains</td>
<td>$x_1: T_{WO,0.55}$, $x_2$: Solar radiation</td>
<td>( y = 83.9 - 4.7x_1 - 0.02x_2 )</td>
<td>0.59</td>
<td>1020</td>
<td>MR R1</td>
<td>1011</td>
<td>-1%</td>
</tr>
<tr>
<td>Winter Test 2: Left House Insulated Test (29/03/2015 - 01/05/2015)</td>
<td>Total internal gains</td>
<td>$x_1: T_{WO,0.55}$, $x_2$: Solar radiation</td>
<td>( y = 88.2 - 5.3x_1 - 0.04x_2 )</td>
<td>0.84</td>
<td>1042</td>
<td>MR R2</td>
<td>1186</td>
<td>14%</td>
</tr>
</tbody>
</table>
\( R^2 \) is a measure of the amount of variance in the dependent variable accounted for by the independent variables in the model. The model MR R2 accounted for 84% of the variance in measured total internal gains (Table 5-3), a well performing model, which in turn predicted total internal gains in a different time period almost exactly. MR R1 only accounted for 59% of the variance in measured total internal gains and therefore produced a worse prediction of total internal gains. The models had different \( R^2 \) values because of the number of days of data they were built on and seasonal differences. MR R2 was built using 33 days of data, compared to MR R1 built using 18 days of data; it is generally accepted that better regression models are built using more data. MR R2 was also built on data from a time period that had a greater range of \( T_{wo} \): 4.9 °C compared to 3.1 °C, and solar radiation: 220 W/m² compared to 126 W/m²; this greater range was captured by MR R2 and made it a more accurate model by allowing it to predict across this range of values.

MR R1 and MR R2 conform to all of the assumptions of regression (Table 5-4, Figure 5-5). This means that there is some correlation in the residuals; this is likely to be because this is time series data: each daily datum has a relationship with that of the past and future day. Preferably this would be included in the model, however to do this, time series analysis would need to be implemented. As described in section 3.7.4 this is complex and beyond the scope of this thesis.

**Table 5-4: Multiple regression models assumptions for the right house**

<table>
<thead>
<tr>
<th>Model</th>
<th>MR R1</th>
<th>MR R2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variable types</strong></td>
<td>Yes Quantitative</td>
<td>Yes Quantitative</td>
</tr>
<tr>
<td><strong>Non-zero variance</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>No perfect multicollinearity:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average VIF must be close to 1</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>VIF = 1.0</td>
<td>VIF = 1.1</td>
</tr>
<tr>
<td><strong>Predictors are uncorrelated with</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>external variables</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Homoscedasticity</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Independent errors:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&lt; Durbin-Watson &lt; 3</td>
<td>Yes: D-W = 1.078</td>
<td>Yes: D-W = 1.495</td>
</tr>
<tr>
<td><strong>Normally distributed errors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Independence</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Linearity</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
5.3.3 Annual energy demand reduction due to IWI

Linear regression models can accurately predict energy demand, demonstrated using data collected in the right house. In order to predict annual energy demand models were built on data from the left house, both before and after the installation of internal wall insulation (Table 5-5). Two models were built:

- **RL1**: built using the data from the left house during Winter Test 1: Matched Pair Test
  
  (R: Regression, L: Left, 1: Winter Test 1)

- **RL2**, built using the data from the left house during Winter Test 2: Left House Insulated Test
  
  (R: Regression, L: Left, 2: Winter Test 2)

Single linear regression models were used instead of multiple linear regression models. Despite attempts to include the effect of solar into the models to match the right house models: MR R1 and MR R2, it did not improve their $R^2$, therefore solar was not explicitly included as a predictor. It is however likely implicitly included because solar has a direct relationship with outdoor temperature. Both the models R L1 and R L2 have high $R^2$ values; the variance in the models is explained well by the single predictor of $T_{wo}$. The models R L2 conforms to all of the assumptions of regression, however R L1 violates the assumption of independent errors (Table 5-6, Figure 5-6).
Table 5-5: Linear regression models for the left house

<table>
<thead>
<tr>
<th></th>
<th>Winter Test 1: Matched Pair Test (17/02/2015 – 06/03/2015)</th>
<th>Winter Test 2: Left House Insulated Test (29/03/2015 – 01/05/2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model built on test data</td>
<td>R L1</td>
<td>R L2</td>
</tr>
<tr>
<td>Dependent variable, y</td>
<td>Total internal gains</td>
<td>Total internal gains</td>
</tr>
<tr>
<td>Independent variable</td>
<td>x: $T_{WO, 0.45}$</td>
<td>x: $T_{WO, 0.8}$</td>
</tr>
<tr>
<td>Model</td>
<td>$y = 92.4 - 5.3x$</td>
<td>$y = 57.4 - 4.3x$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.67</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Table 5-6: Regression models assumptions for the left house

<table>
<thead>
<tr>
<th></th>
<th>R L1</th>
<th>R L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable types</td>
<td>Yes Quantitative</td>
<td>Yes Quantitative</td>
</tr>
<tr>
<td>Non-zero variance</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Predictors are uncorrelated with external variables</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Homoscedasticity</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Independent errors:</td>
<td>No: D-W = 0.747</td>
<td>Yes: D-W = 1.463</td>
</tr>
<tr>
<td>1&lt; Durbin-Watson &lt; 3</td>
<td>D-W = 0.747</td>
<td>D-W = 1.463</td>
</tr>
<tr>
<td>Normally distributed errors</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Independence</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Linearity</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Models R L1 and R L2 use different alpha values to one another for the calculation of $T_{wo}$ (Equations 16 and 17). R L1 used an alpha of 0.45 whereas R L2 required an alpha of 0.8. Alpha controls the size of the time lag in the equation. The higher alpha value used in R L2 shows that once insulated the left house in winter has a greater relationship to the temperature of the past; this is reasonable as the insulation slows heat transfer.

The linear regression models were used to calculate annual energy demand in a house with and without IWI. The annual central heating demand and gas consumption of the left house before and after IWI were calculated (Table 5-7) using the regression models produced from measured data (Table 5-5). The independent variable $T_{wo}$ was calculated from a CIBSE Test Reference Year (section 3.7.8). The central heating demand was calculated for the UK winter heating season: October – April. The regression model uses the exponentially weighted outdoor running mean temperature to predict total internal gains, from this the gains from people and appliances were subtracted, at 12kWh per day, to give central heating demand. The central heating demand was multiplied by the average boiler efficiency of the two houses - 86% to give gas consumption. Then average boiler efficiency was calculated from the measured gas consumption and heat consumption.

**Table 5-7: Annual energy demand of the left house extrapolated from measured data**

<table>
<thead>
<tr>
<th></th>
<th>Winter energy demand calculated using regression models</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uninsulated</td>
<td>Internal Wall Insulation</td>
<td>Reduction due to IWI</td>
</tr>
<tr>
<td>Model used for prediction</td>
<td>R L1</td>
<td>R L2</td>
<td>-</td>
</tr>
<tr>
<td>Central heating demand (kWh)</td>
<td>9735 ± 1363</td>
<td>4703 ± 658</td>
<td>5032 (52%)</td>
</tr>
<tr>
<td>Gas consumption (kWh)</td>
<td>11320 ± 1585</td>
<td>5468 ± 765</td>
<td>5852(52%)</td>
</tr>
</tbody>
</table>

Figure 5-6: Residuals from the left house regression models

Figure 5-6 shows the residuals from the regression models for the left house. Models R L1 and R L2 use different alpha values to one another for the calculation of $T_{wo}$ (Equations 16 and 17). R L1 used an alpha of 0.45 whereas R L2 required an alpha of 0.8. Alpha controls the size of the time lag in the equation. The higher alpha value used in R L2 shows that once insulated the left house in winter has a greater relationship to the temperature of the past; this is reasonable as the insulation slows heat transfer.
Installing internal wall insulation resulted in a reduction in gas consumption of 52% over the heating season, a significant saving. It is difficult to assess the accuracy of the regression models, and therefore their outputs. By referring back to those used to test the method for the right house (Table 5-3) it can be seen that the model MR R1 that explained 59% of the variance predicted internal heat to an accuracy of 14%. R-L1 with an $R^2$ of 67% and R L2 with an $R^2$ of 72%, will predict much better than MR R1, but a conservative estimate of accuracy of 14% could be attributed to the models.

5.4 Modelled annual energy demand using RdSAP

Predictions of energy demand were made using RdSAP. Predictions were then compared to the annual energy demand extrapolated from measured data to identify any performance gap. RdSAP models of the left house both with and without IWI were built using The Government’s Standard Assessment Procedure for Energy Rating of Dwellings (DECC 2013), using the method described in section 3.8.1. Two sets of models were built, producing two sets of heat demand prediction: the first were ‘typical RdSAP models’ using standard RdSAP assumptions and the second were ‘improved RdSAP models’ using measured air permeability and wall $U$-values. The total heat demand for the UK winter heating season: October- April are presented (although it is noted that in RdSAP the heating season is usually October-May).

The central heating demand of the left house with and without IWI, calculated using typical and improved RdSAP models, are presented in Table 5-7. The RdSAP models accurately predict the percentage reduction in energy demand due to IWI. The typical RdSAP model predicted a 48% reduction in central heating demand due to the installation of IWI; the improved RdSAP model predicted a 57% reduction. Both of the RdSAP models predicted the percentage energy saving accurately when compared to the measured annual reduction in central heating demand of 52% (Table 5-7).

**Table 5-8: Annual heat demand of the left house calculated using RdSAP**

<table>
<thead>
<tr>
<th>Insulation state</th>
<th>Measured</th>
<th>Modeled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Extrapolated using linear regression</td>
<td>Typical RdSAP model</td>
</tr>
<tr>
<td></td>
<td>Annual central heating demand (kWh)</td>
<td>Annual central heating demand (kWh)</td>
</tr>
<tr>
<td>Uninsulated</td>
<td>9735</td>
<td>16187</td>
</tr>
<tr>
<td>IWI</td>
<td>4703</td>
<td>8379</td>
</tr>
<tr>
<td>Reduction in left house</td>
<td>5032 (52%)</td>
<td>7808 (48%)</td>
</tr>
</tbody>
</table>
However, the RdSAP models do not accurately predict the absolute values of energy demand and therefore energy savings (Table 5-7). The typical RdSAP model seriously over-predicts energy demand of the house when uninsulated and when IWI is installed. The improved RdSAP which includes measured air tightness values and wall U-values, predicts the central heating demand of both the uninsulated and internally insulated houses much more accurately than the typical RdSAP model, but still poorly. This is because despite the inputs of air tightness values and wall U-values the HTC of the houses are still incorrect (section 4.5.2). The RdSAP calculated HTC is the most inaccurate in the typical RdSAP model for the uninsulated house: by 47%; this results in an energy demand over-prediction of 66%. However, the RdSAP calculated HTC is very accurate in the improved RdSAP model for the internally insulated house; this model still over-predicts energy demand by 29%. These RdSAP predictions are out of the proposed uncertainty of the regression predictions of 14%.

The RdSAP models’ inputs were similar to those of the test houses, including the heating set-point temperature, the heating schedule, the outdoor temperature and the occupancy gains. The improved RdSAP models also incorporated measured air permeabilities and wall U-values. The indoor temperatures were calculated in the RdSAP models from heating system set-points, heating system schedules, indoor gains and outdoor temperatures. The set-point of 21°C and the heating system schedule used in the test houses was also used in RdSAP. Measured internal temperatures were calculated instead of input into the improved RdSAP model because they were only available for test periods, not the whole year; however the measured temperatures of each test period were compared to the modelled indoor temperatures of the corresponding month and found to be within 0.5°C. The weather used for calculating the winter energy demand in RdSAP and that from the CIBSE TRY, used to extrapolate measured data to annual energy demand, were similar. The average outdoor temperature for October to April in SAP was 6.6 °C, whereas the CIBSE TRY’s was 6.3 °C; despite the lower outdoor air temperature the regression model predicted much lower heat demand. The synthetic occupancy gains used in the winter tests that led to the production of the regression model were 11% higher than those in RdSAP, however this is a small amount of heat when considering the total heat gains (Table 5-1).

RdSAP is predicting energy demand inaccurately. The factors that control the energy demand of the test houses were accurately reflected in the inputs to the model. The inaccurate prediction of heating demand produced by the improved RdSAP model of the house with IWI, despite accurate inputs of temperatures, occupancy gains and the HTC indicates that RdSAP predicts energy demand poorly in these houses. This performance gap between modelled and measured values in these houses could be an issue if RdSAP was used as a design tool for retrofit. The performance gap over-predicts absolute energy savings and therefore the CO₂ savings from the retrofit of IWI. However, RdSAP predicts percentage reduction in energy demand well.

5.5 Chapter Summary

The left house of a pair of thermally matched houses had internal wall insulation applied. A side-by-side comparison of the pair of houses in April 2015 showed that the house with IWI required 46% less heat gains
(the heat from the heating system plus internal gains and solar gains) than the uninsulated house to achieve an average temperature 1°C warmer. IWI was very effective at reducing heat demand. The side-by-side comparison of the uninsulated houses showed that the left house had 10% higher total heat gains and had an air temperature on average 0.1°C warmer, this was due to the uncertainties of the measurements and inaccuracies of the calculation methods.

The measured energy demand data were extrapolated into a year of energy demand. A degree-day model and a linear regression model were tested as tools to perform the extrapolation. It was found that the degree-day model predicted energy demand inaccurately. The linear regression model predicted energy demand accurately. The regression models were therefore used to extrapolate the measured data into yearly central heating demand using the CIBSE TRY for Nottingham. In the left test house internal wall insulation resulted in a reduction in gas consumption of 52% over a UK winter heating season from October to April.

To identify any performance gap, measured central heating demand was compared to RdSAP calculated central heating demand. A typical RdSAP model over-predicted central heating demand in the uninsulated house by 66% and internally insulated house by 78%. The model also over-predicted the savings due to retrofit by 55%. However the RdSAP model predicted the percentage reduction in energy demand well. As discussed in Section 2.3.3, this has detrimental implications for the effectiveness of energy efficiency schemes.
6 The impact of IWI on summer overheating

6.1 Introduction

The purpose of this chapter is to answer the research questions: does the retrofit of internal wall insulation in solid wall houses cause overheating and could high indoor temperatures be prevented from occurring using a simple mitigation strategy? This is in fulfilment of Objective 5. Indoor operative temperature data were collected in the test house during the summer of 2015, in three test periods: Summer Test 1: Left House Insulated Test; Summer Test 2: Mitigation Test; and Summer Test 3: Matched Pair Test, the method is detailed in Section 3.6. A side-by-side comparison was done of the operative temperature data from the two houses in all three tests. The Matched Pair Test was used to identify whether the houses performed as a matched pair in summer (section 6.2). The Left House Insulated Test was used to identify whether IWI increased indoor operative temperature and discover whether overheating occurred (section 6.3). The Mitigation Test was used identify whether a simple low-cost mitigation strategy would make indoor operative temperatures in the houses more similar (section 6.4). Linear regression was used to compare the data from the Left House Insulated Test and the Mitigation Test, demonstrating the effectiveness of the mitigation strategy (section 6.6). Future weather data were then used to predict future indoor operative temperatures in the houses, and the limits of the mitigation strategy (section 6.7).

6.2 Summer side-by-side comparison of Summer Test 3: Matched Pair Test

The results of the Matched Pair Test are presented first to assess how well the houses were matched before internal wall insulation was applied. The internal gains supplied by the synthetic occupancy system to represent those from people and appliances were measured in each test to review whether the gains were similar that were provided to each house. These are detailed in Table 6-1; the gains were never identical due to the heat emitters of the synthetic occupancy equipment failing, but the largest average difference between the houses was 1.3 kWh. Considering the overall gains including solar, which are estimated during Summer Test 2 to be on average 13 kWh through the windows alone, this difference is only 5% of total gains, unlikely to make a large difference in indoor temperature.

In the living rooms the indoor operative temperatures of the two houses were very similar when both had no insulation applied (Figure 6-1); whereas there was more variability between the main bedrooms. Differences in operative temperature between the houses was variable, small differences often occurred when the houses were experiencing solar gains under 500 W/m² and a small diurnal swing in outdoor air temperature. The difference between the houses occurs due to their different orientations, both faced south-southeast, but the living room and main bedroom had a differently orientated side wall. The left house had a west-southwest facing side wall, receiving sun throughout the afternoon, resulting in higher temperatures in the bedrooms. The living room on the ground floor was shaded by the adjacent house, so received less afternoon sun, resulting in more similar indoor temperatures.
Table 6-1: Internal gains from synthetic occupancy in summer

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Left</th>
<th>Right</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer Test 3: Matched Pair Test (19/08/2015-08/09/2015)</td>
<td>10.8</td>
<td>11.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Summer Test 1: Left House Insulated Test (05/06/2015-03/07/2015)</td>
<td>9.9</td>
<td>10.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Summer Test 2: Mitigation Test (11/07/2015-31/07/2015)</td>
<td>10.3</td>
<td>11.6</td>
<td>1.3</td>
</tr>
</tbody>
</table>

The living rooms across the two houses experienced similar mean, minimum and maximum operative temperatures during occupied hours (Table 6-2, Figure 6-2); with differences of 0.5 °C, 0.5 °C and 0.6 °C respectively. The mean absolute difference between the living rooms was 0.5 °C, by comparing this to the mean it is evident that the left house was always warmer than the right. Despite the differences that can be seen in Figure 6-1, when focussing on occupied hours, the bedrooms of the two houses were also very similar in temperature, with a difference between the houses of 0.5 °C in the mean and minimum operative temperatures and a mean absolute difference of 0.5 °C (Table 6-2). However the difference between the maximum temperatures measured was 1.2 °C, in warmer spells of weather with more solar radiation the difference between the houses could be more noticeable.
Figure 6-1: Matched Pair Test Indoor operative temperature, outdoor air temperature and horizontal solar radiation
| Table 6-2: Descriptive statistics of indoor operative temperature, outdoor air temperature and solar radiation in occupied periods |
| --- | --- | --- | --- | --- | --- | --- |
| | Mean | Standard Deviation | Minimum | Maximum | Range | Mean Absolute Difference |
| Summer Test 3 | Day | Living Room Operative Temperature (°C) | Left | 20.9 | 1.7 | 17.1 | 25.1 | 8.0 | 0.5 |
| | | Right | 20.5 | 1.7 | 16.6 | 24.5 | 7.8 | |
| | Outdoor Air Temperature (°C) | 16.4 | 3.7 | 7.2 | 30.1 | 22.9 | |
| | Night | Main Bedroom Operative Temperature (°C) | Left | 20.2 | 2.1 | 16.8 | 25.0 | 8.2 | 0.5 |
| | | Right | 19.7 | 2.0 | 16.3 | 23.8 | 7.6 | |
| | Outdoor Air Temperature (°C) | 12.3 | 3.2 | 4.5 | 21.9 | 17.4 | |
| | All hours | Horizontal Solar Radiation (W/m²) | 134 | 208 | 0 | 1164 | 1164 | |
| Summer Test 1 | Day | Living Room Operative Temperature (°C) | Left | 22.8 | 1.9 | 18.7 | 28.0 | 9.3 | 2.2 |
| | | Right | 20.6 | 2.1 | 16.8 | 26.2 | 9.5 | |
| | Outdoor Air Temperature (°C) | 17.8 | 4.6 | 7.7 | 35.0 | 27.3 | |
| | Night | Main Bedroom Operative Temperature (°C) | Left | 22.2 | 2.4 | 18.5 | 28.8 | 10.3 | 1.5 |
| | | Right | 20.7 | 2.5 | 17.3 | 27.8 | 10.4 | |
| | Outdoor Air Temperature (°C) | 12.0 | 3.5 | 4.2 | 25.4 | 21.2 | |
| | All hours | Horizontal Solar Radiation (W/m²) | 222 | 292 | 0 | 1393 | 1393 | |
| Summer Test 2 | Day | Living Room Operative Temperature (°C) | Left | 21.3 | 1.6 | 16.7 | 23.9 | 7.2 | 1.1 |
| | | Right | 20.2 | 1.5 | 16.3 | 22.8 | 6.6 | |
| | Outdoor Air Temperature (°C) | 17.6 | 2.9 | 10.5 | 24.6 | 14.1 | |
| | Night | Main Bedroom Operative Temperature (°C) | Left | 18.4 | 1.9 | 14.2 | 21.6 | 7.4 | 0.5 |
| | | Right | 18.3 | 1.8 | 14.1 | 21.4 | 7.3 | |
| | Outdoor Air Temperature (°C) | 12.6 | 2.4 | 5.3 | 17.4 | 12.0 | |
| | All hours | Horizontal Solar Radiation (W/m²) | 179 | 248 | 0 | 1238 | 1238 | |
Figure 6-2: Box and whisker plots of living room and main bedroom operative temperature and outdoor air temperature.

Box and whisker plots are a graphical representation of the operative temperatures. From the bottom of each, the crossbar of the downwards extending line indicates the minimum, the bottom of the box indicates the 25th percentile, the line across the box indicates the median, the top of the box indicates the 75th percentile, the crossbar of the upwards extending line indicates the maximum value and the cross indicates the mean.
6.3 Summer side-by-side comparison of Summer Test 1: Left House Insulated Test

These results demonstrate the difference in indoor temperature between a house with and without IWI. During Summer Test 1 the indoor operative temperatures were consistently higher in the left house fitted with IWI, compared to the uninsulated right house (Figure 6-3). During occupied hours (8.30: 23.00) the left house living room was significantly warmer, with a mean absolute difference of 2.2 °C and an average difference in maximum temperature of 1.8 °C (Table 6-2, Figure 6-2). The left house in Summer Test 1 performed more differently to the right house than in Summer Test 3: Matched Pair Test. Without normalising for the weather
the indoor temperatures cannot be compared across the two tests. However the mean absolute difference between the living rooms was only 0.5 °C when both houses were uninsulated, whereas it is 4 times as much when IWI is installed, this extra temperature difference was due to the internal wall insulation.

Table 6-3: Amount of overheating during each test in occupied hours

<table>
<thead>
<tr>
<th></th>
<th>Overheating in the living Rooms, assessed using TM52 Cat I criteria</th>
<th>Overheating in the bedrooms, assessed using threshold of 26 °C for less than 3% of hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Criterion 1</td>
<td>Criterion 2</td>
</tr>
<tr>
<td>Left House Insulated Test</td>
<td>Left house (HTC = 149)</td>
<td>4.7 %</td>
</tr>
<tr>
<td></td>
<td>Right house (HTC = 240)</td>
<td>0 %</td>
</tr>
<tr>
<td>Mitigation Test</td>
<td>Left house (HTC = 149)</td>
<td>0 %</td>
</tr>
<tr>
<td></td>
<td>Right house (HTC = 240)</td>
<td>0 %</td>
</tr>
</tbody>
</table>

The CIBSE TM52 adaptive criteria for defining overheating in free-running buildings (CIBSE, 2013) was used to assess whether overheating occurred during occupied hours in the living rooms. There are three criteria and overheating is said to occur when any two of these criteria are not satisfied, this is detailed in Section 3.7.3. The living room of the left insulated house overheated according to CIBSE TM52 Cat I overheating criteria (Table 6-3). It failed on both criterion 1: the operative temperature in the living room exceeded $T_{\text{max}}$ Cat I for 4.7% of occupied hours (Figure 6-3, Table 6-3); and on criterion 2, the weighted exceedance, on the 1st July. The living room in the right, uninsulated house passed the TM52 overheating criteria, not exceeding $T_{\text{max}}$ Cat I at any point during testing; therefore comparing the living rooms the left house with IWI failed the overheating test whereas the right house without IWI passed. There are two caveats to this finding. Firstly, at the end of Summer Test 1 there was an exceptionally hot period of weather: the average outdoor temperature on the 1st July 2015 was 26.7 °C, the hottest average temperature for the preceding 10 years; without this period of exceptionally hot weather overheating would not have occurred. Secondly, the Cat I criteria were used to assess overheating, this is for people with a “High level of expectation only used for spaces occupied by very sensitive and fragile persons” (CIBSE, 2013); this was used due to the test being for elderly residents for whom the impacts of hot weather are worse. If instead the Cat II criteria are used for which the temperature limits are 1 °C higher than Cat I, the house with IWI would have passed the overheating test.
During occupied hours (23.00:7.30) the main bedrooms in this test had a mean absolute difference in operative temperature of 1.5 °C (Table 6-2); three times that of the matched pair test. Figure 6-3 shows that the bedrooms performed differently, with more rapid increases and decreases in temperature in the bedroom with IWI. Much of this variation occurs in the day when the bedrooms are considered unoccupied. The main bedroom of the left, insulated house exceeded the night time overheating threshold of 26 °C for 12.3% of total occupied hours (Figure 6-3, Table 6-3), the threshold was surpassed every night from the 30th June-3rd July. The main bedroom of the right, uninsulated house exceeded the threshold of 26 °C for 4.2% of total occupied hours. Therefore, both main bedrooms overheated due to exceeding the threshold of 3% of total occupied hours above 26 °C; the bedroom with IWI overheated over 2.5 times more frequently than the uninsulated bedroom.

6.4 Summer side-by-side comparison of Summer Test 2: Mitigation Test

These results present the effectiveness of the mitigation strategy consisting of day-time shading and night ventilation, described in section 3.6.1. With the mitigation strategy applied in Summer Test 2 the living room in the left, insulated house continued to experience higher operative temperatures than the living room in the uninsulated house (Figure 6-4). During occupied hours the left living room was significantly warmer than the right, with a MAD in operative temperature of 1.1 °C. Despite this difference, neither living room overheated according to CIBSE TMS2 Cat I overheating criteria (Figure 6-4, Table 6-3). However it must be noted that the outdoor temperatures in Summer Test 2 were much lower than those in Summer Test 1 where overheating did occur (Table 6-2), therefore a precise comparison cannot be made without normalisation. Each night, when unoccupied, the temperatures in the two living rooms reduce to almost the same level. This demonstrates the success of the mitigation strategy: the house with IWI cools down over night to the level of an uninsulated house, so that the next day the temperature does not get as high.

During occupied hours at night, the operative temperatures in both bedrooms, insulated and uninsulated, are almost the same (Table 6-2); the difference between the maximum temperatures was only 0.2 °C. Both the left and the right bedroom were warmer at different times during Summer Test 2 (Figure 6-4); further proven by an MAD of 0.5 °C, which captures the absolute value of variation, but a difference between the means of only 0.1 °C (Table 6-2). This is reasonable as the indoor temperature in the bedrooms was driven by outdoor air temperature due to the opening of windows at night as part of the mitigation strategy. No overheating occurred in either bedroom during the Mitigation Test (Table 6-3).
Figure 6-4: Mitigation Test Indoor operative temperature, outdoor air temperature and horizontal solar radiation

6.5 Swings in indoor operative temperature

During the Matched Pair Test similar daily swings in operative temperature were observed in the left house and right house living rooms (Figure 6-5). However, the left house main bedroom had a larger swing in operative temperature than that of the right bedroom, despite the houses being a matched pair. This difference occurred because of the differing orientations of the side walls, as discussed in 6.2. Both of the living rooms’ temperatures increased and decreased at a faster rate than the main bedrooms’ temperatures (Figure 6-1). This is likely due to the combined effect of solar and internal gains: throughout the day the living rooms had synthetic occupancy applied, there were solar gains through the large bay windows, and outdoor
air temperature was at its peak. In the living rooms at night there were no solar gains, no occupants and outdoor air temperature was decreasing, therefore the indoor air cooled rapidly. During the day, the main bedroom was ‘unoccupied’, and therefore had only solar gains and outdoor air temperature to raise the indoor air temperature. However, at night synthetic occupancy slowed the cooling of the room that would have occurred due to the drop in outdoor air temperature.

Figure 6-5: Daily swings in indoor operative temperature

Once the left house was internally insulated, it had a 1 °C average larger daily operative temperature swing than the uninsulated house (Figure 6-5), this is likely the effect of the insulation as they were well matched for swing with a difference of only 0.2 °C during Summer Test 3. The operative temperatures both increase and decrease more quickly in the living room of the left house, which occurred because of the isolation of the thermal mass from the air in the room. The main bedrooms still had a smaller daily average swing than the living rooms, due to only being occupied at night, and were still well matched despite the installation of IWI. The swings were marginally lower for both bedrooms in Summer Test 1 than in the matched pair test, this is assumed to be a variation due to the weather conditions that happened to occur. However, a larger diurnal swing was observed in the bedrooms when there were higher solar gains.

When the left house was insulated the mitigation strategy barely affected the temperature swing in the living rooms (Figure 6-5). Conversely, the temperature swing in both the insulated and uninsulated main bedrooms more than doubled when a mitigation strategy was applied, with a larger swing still observed in the left, insulated house. In the bedrooms the maximum temperatures that occurred during the day appear similar across Summer Test 1 and 2; but the introduction of large quantities of cool night time air as part of the mitigation strategy in Summer Test 2 leads to much lower minimum operative temperatures resulting in larger
swings. In Summer Test 1 the difference between the houses’ swings were 0.5 °C, this increased to 0.8 °C in Summer Test 2; although this is minor this could be explained by the principle that night purging of heat is best in light-weight structures. Here where the IWI has isolated the thermal mass of the brick and plaster walls from the air in the room less heat is stored in the mass and therefore when the air is replaced the operative temperature drops more rapidly.

6.6 Summer cross-test comparison

To assess the effectiveness of the mitigation strategy (section 3.6.1) in each house the indoor operative temperatures from Summer Tests 1 and 2 were compared. The average outdoor air temperatures that occurred during Summer Tests 1 and 2 were similar (Table 6-2); however the maximum temperatures were very different, a maximum of 35 °C occurred during Summer Test 1, a maximum of only 24.6 °C during Summer Test 2. Different levels of solar radiation also occurred during the three tests (Table 6-2). The measured indoor operative temperatures with and without the mitigation strategy cannot be compared directly to one another due to these differences in weather conditions, therefore a model was required for the comparison.

Linear regression models were tested using the method described in section 3.7.6 and the relationships between the indoor operative temperature and the tested predictor variables are displayed in Table 6-4. The exponentially weighted outdoor running mean temperature ($T_{wo}$) (Equations 16 and 17) had the best linear relationship with indoor air temperature in all cases, the mean outdoor air temperature was also a very good predictor. The predictive power of $T_{wo}$ demonstrates that the indoor operative temperatures of the houses were dependent on both current and past days of outdoor air temperature. Multiple regression was also trialled with all variables in an attempt to create improved models; there were none that offered a better $R^2$ and did not violate regression assumptions, usually because the weather variables violated the assumption of no multicollinearity.

Many different versions of $T_{wo}$ were trialled to find the best performing regression model by using different $\alpha$ values, resulting in each room in each test having a different $T_{wo}$ ranging from 0.52-0.65. However in order to plot the data on the same graph the exponentially weighted outdoor running mean temperature with an $\alpha$ of 0.6 was used $T_{wo,0.6}$ because this represented the data from all houses satisfactorily.

The resulting regression models using $T_{wo}$ to compare indoor operative temperature can be seen in Figure 6-6. Indoor operative temperatures were dramatically reduced in both houses in the day and at night through the use of the mitigation strategy. The mitigation strategy becomes ineffective at very high exponentially weighted outdoor running mean temperatures, this can be identified in Figure 6-6 where the lines of best fit for each house from Summer Test 1 and 2 converge in the bedrooms and intersect in the living rooms. It is the night-ventilation component of the mitigation strategy that becomes ineffective; when the outdoor air is warm its cooling effect when replacing warm indoor air is limited. In the uninsulated living room the mitigation strategy was no longer effective at an exponentially weighted outdoor running mean temperature higher than 19.9 °C: the room would be cooler without the mitigation. Comparatively, in the internally insulated living room the
mitigation strategy becomes no longer effective at an exponentially weighted outdoor running mean temperature above 21.6 °C; the indoor temperature is higher, therefore warmer outdoor air can be used to cool the room. The $T_{WO,0.6}$ of the 10 summers prior to this study can be seen in the top box plot of each graph in Figure 6-6. Analysis of this data revealed that there have been only 35 days (2.3% of summer days) where the exponentially weighted outdoor running mean temperature exceeded 19.9 °C and only 8 days (0.5% of summer days) when it exceeded 21.6 °C. These were rare events in the years 2006-2015, therefore the mitigation strategy would have been effective at reducing indoor temperatures most days in both houses. The living room of the uninsulated house was always cooler than the house with IWI (Figure 6-6), it would be more comfortable in warmer weather to live in a house with no insulation.

In the main bedrooms, during occupied hours, the mitigation strategy was always effective at reducing indoor operative temperature, in both the insulated and uninsulated houses, demonstrated by no intersection of the lines of best fit in Figure 6-6. As shown previously from the descriptive statistics, the operative temperatures of the two bedrooms with the mitigation strategy were almost identical; a house with IWI could provide an environment as comfortable as an uninsulated house at night provided simple low-cost mitigation strategies were employed.

The higher operative temperatures observed in the insulated house when compared to the uninsulated house in Summer Test 1 were due to both thermal transmittance and thermal storage. The installation of IWI reduced the walls ability to transmit heat which resulted in the left house cooling more slowly when the outdoor temperature was lower than the indoor temperature. Conversely when the outdoor temperature was significantly higher than the indoor temperature, which occurred on the 30th June and 1st July the internal wall insulation reduced the flow of warmth from the outdoors in. The IWI also lower the available thermal capacity of the walls by isolating the thermal mass of the external brick walls from the air in the house. In the uninsulated house the thermal mass of the walls absorbed some of the heat from the air, so the operative temperature did not increase as much.

Both the night ventilation and the solar shading components of the mitigation strategy (section 3.6) contributed to the reduction in the operative temperature in the living rooms in Summer Test 2. The use of solar shading reduced the solar gains which if they were present would have contributed to the increase in operative temperature. The night ventilation strategy also had a clear effect on temperature on the ground floor of the house, despite it being only implemented on the first floor. The temperatures in the living rooms were the same in the Mitigation Test at night (Figure 6-4); the night ventilation allowed the houses to cool to the same level at night before gains are introduced the next day. There was still a difference between the two living rooms in the Mitigation Test because the house with IWI lost less heat through the walls and had less available thermal mass to absorb heat in the day.

In the main bedrooms during the Mitigation Test the night ventilation strategy was the primary method of cooling, not heat loss through the walls; the decrease in thermal transmittance due to IWI had little effect on operative temperature. Most nights the minimum operative temperature was lower in the house with IWI
than the uninsulated house, the house with IWI also often cooled at a faster rate (Figure 6-4) this was due to the reduction of thermal mass in contact with the air in the room. In the uninsulated house the heat stored in the walls was released to increase the temperature of the cool night air entering the rooms. However in the insulated house plasterboard and insulation material has little thermal capacity and any heat available in the brick mass of the wall had to be transmitted through the insulation to reach the air in order to warm it. It may be a benefit of IWI that the room cools more quickly and to a lower temperature.

Table 6-4: Summer regression results

<table>
<thead>
<tr>
<th></th>
<th>Living Room Operative Temperature: 8.30:23.00 (°C)</th>
<th>Living Room Operative Temperature: 23.00:7.30 (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer Test 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left insulated</td>
<td>Mean Outdoor Air Temperature (°C)</td>
<td>Mean Outdoor Air Temperature (°C)</td>
</tr>
<tr>
<td></td>
<td>0.84 0.80 0.59 0.62 0.24 0.28 -0.02 -0.47 -0.20 0.96</td>
<td>0.91 0.65 0.65 0.05 0.27 0.18 0.12 -0.03 -0.19 -0.29 0.99</td>
</tr>
<tr>
<td>Right</td>
<td>0.84 0.83 0.53 0.62 0.26 0.34 -0.06 -0.48 -0.23 0.95</td>
<td>0.89 0.69 0.56 0.15 0.32 0.22 0.16 -0.10 -0.20 -0.26 0.98</td>
</tr>
<tr>
<td>No mitigation</td>
<td>Main Bedroom Operative Temperature: 23.00:7.30 (°C)</td>
<td>Main Bedroom Operative Temperature: 23.00:7.30 (°C)</td>
</tr>
<tr>
<td>(05/06/2015-03/07/2015)</td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td></td>
<td>Mean Outdoor Air Temperature (°C)</td>
<td>Mean Outdoor Air Temperature (°C)</td>
</tr>
<tr>
<td></td>
<td>0.88 0.89 0.73 0.52 0.34 0.30 0.30 -0.05 -0.45 0.10 0.98</td>
<td>0.87 0.87 0.74 0.47 0.30 0.28 0.28 -0.08 -0.42 0.11 0.98</td>
</tr>
<tr>
<td></td>
<td>Minimum Outdoor Air Temperature (°C)</td>
<td>Minimum Outdoor Air Temperature (°C)</td>
</tr>
<tr>
<td></td>
<td>0.84 0.83 0.53 0.62 0.26 0.34 -0.06 -0.48 -0.23 0.95</td>
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<td>0.91 0.71 0.74 0.08 0.15 0.16 0.10 -0.11 -0.14 -0.21 0.96</td>
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<tr>
<td></td>
<td>0.87 0.69 0.74 0.10 0.10 0.21 0.16 -0.21 -0.15 -0.13 0.91</td>
<td>0.87 0.69 0.70 0.10 0.10 0.21 0.16 -0.21 -0.15 -0.13 0.91</td>
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<td>Maximum Outdoor Air Temperature (°C)</td>
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<td></td>
<td>0.91 0.71 0.74 0.08 0.15 0.16 0.10 -0.11 -0.14 -0.21 0.96</td>
<td>0.91 0.71 0.74 0.08 0.15 0.16 0.10 -0.11 -0.14 -0.21 0.96</td>
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<td></td>
<td>0.87 0.69 0.70 0.10 0.10 0.21 0.16 -0.21 -0.15 -0.13 0.91</td>
<td>0.87 0.69 0.70 0.10 0.10 0.21 0.16 -0.21 -0.15 -0.13 0.91</td>
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<td>0.91 0.71 0.74 0.08 0.15 0.16 0.10 -0.11 -0.14 -0.21 0.96</td>
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<td></td>
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<td>0.87 0.69 0.70 0.10 0.10 0.21 0.16 -0.21 -0.15 -0.13 0.91</td>
</tr>
<tr>
<td></td>
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<td>0.91 0.71 0.74 0.08 0.15 0.16 0.10 -0.11 -0.14 -0.21 0.96</td>
<td>0.91 0.71 0.74 0.08 0.15 0.16 0.10 -0.11 -0.14 -0.21 0.96</td>
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</tbody>
</table>
Figure 6-6: Indoor operative temperature in the Left House Insulated Test and the Mitigation Test regressed against exponentially weighted outdoor running mean temperature, with boxplots of current and future predicted weather.
6.7 Current and future overheating likelihood

The tests took place in 2015, which was slightly cooler than the thirty year average of summers, but with an exceptionally warm period: 1\[^{st}\]-3\[^{rd}\] July. The top boxplots in each graph in Figure 6-6 show that higher values of the exponentially weighted outdoor running mean temperature (T\(_{\text{WO}}\)) rarely occurred between the years 2006-2015. The 1\[^{st}\] July 2015 had the 13\[^{th}\] highest T\(_{\text{WO}}\) of the 2006-2015 summers (consisting 1530 days) and this was the only day in Test 1 that criterion II of the CIBSE TM52 was surpassed. Therefore the overheating that occurred in the living room on this day was an unusual event that would not have occurred often in the 10 years prior to the test.

To explore this further, the result was compared with the exponentially weighted outdoor running mean temperatures for future weather scenarios (Figure 6-6); the 2036-2065 predictions are the central box-plots and the 2066-2095 predictions are those at the bottom. These were produced using the method detailed in Section 3.7.8. It is not possible to predict levels of overheating directly using future weather data because models would be required to predict hourly indoor temperatures trained on the data collected. There are no reliable models that currently do this as discussed in 3.7.4. However, by comparing future weather data to that of the 2006-2015 an idea of future impact can be gained. The median T\(_{\text{WO}}\) of the future weather scenario predictions for 2036-2065 is less than 1\(^\circ\)C higher than that of the 2006-2015 observations. It is therefore likely that similar levels of overheating to those observed in the tests might be expected up to the year 2065. It is not possible to do any further analysis at this stage and this is an area for future work.

The predicted temperatures for 2066-2095 are much warmer, with an increase in the median temperature of 3\(^\circ\)C and an increase in the maximum of 3.5\(^\circ\)C compared to the period 2006-2015. Most interestingly is the shift in the 75\% quartile, the conditions of the days from 1\[^{st}\]-3\[^{rd}\] July where overheating occurred are on this boundary. Overheating occurred in the left living room on the 3\[^{rd}\] July with a T\(_{\text{WO}}\) 19.8 \(^\circ\)C, it can be roughly estimated that around this value of T\(_{\text{WO}}\) at or above this overheating would occur; therefore in the time period 2066-2095 over 27\% of summer days could experience overheating in the internally insulated living room. The mitigation strategy of night ventilation and solar shading would no longer be effective in the living room for 9\% of summer days, averaging at 14 days every summer. In Summer Test 1 the bedroom with IWI overheated from 30\[^{th}\] June – 3\[^{rd}\] July, the lowest T\(_{\text{WO}}\) during this period was 19.8 \(^\circ\)C, between 2066-2095 the insulated bedroom would overheat 27\% of evenings without any mitigation; however the mitigation strategy would likely be effective at reducing indoor operative temperatures in all summer days through to 2095.

6.8 Chapter Summary

Indoor operative temperature data were collected from a pair of semi-detached pre-1919 built houses in Leicestershire in the summer of 2015. Three different tests were done: the Matched Pair Test, the Left House Insulated Test and the Mitigation Test. The Matched Pair Test was used to verify whether the houses were a matched pair; it was found that both the living room and the main bedroom of the left house during occupied hours were on average 0.5 \(^\circ\)C warmer than the right house. This was due to the orientation of the houses, as
the left house had a west-southwest facing side wall, resulting in higher gains. The houses would therefore not be considered perfectly matched, however the knowledge of the difference in temperature allowed inferences to be drawn once one house was internally insulated.

The retrofit of internal wall insulation increased the indoor operative temperature of both the living room and main bedroom in the left house in the Left House Insulated Test; the difference between the houses increased to 2.2 °C in the living rooms and 1.5 °C in the main bedrooms during occupied hours. A difference this large was clearly due to the insulation and not the house orientations. Some overheating was measured in the house with IWI, however this occurred in an unusually hot period of weather; analysis of the climate between the years 2006-2065 shows the house with IWI is unlikely to overheat under the current climate or immediate future climate. However further into the future IWI would no longer be suitable, using a weather scenario produced using the UKCP09 weather generator ‘medium emissions’ scenario it was calculated that the house would overheat on over a quarter of summer days.

In the Mitigation Test solar shading was used in the living room and main bedroom and a night ventilation strategy was employed at night on the first floor. The mitigation strategy reduced high indoor operative temperatures and no overheating occurred in either house. The night ventilation was very successful; temperatures during occupied hours at night in the bedrooms were the same with or without IWI. The combined strategy was also very successful in the living rooms, however the house with IWI was still 1.1°C warmer during occupied hours. Tested using the future weather scenarios the mitigation strategy would continue to be effective at providing night time comfort into the 2090s.
7 Discussion

7.1 Introduction

This chapter explores the current state of internal wall insulation, how often it is used and where its future lies (section 7.2). This includes an analysis of whether or not IWI is an appropriate technique to save energy and meet carbon reduction targets (section 7.3). There is an examination of current models, the implications of poorly performing models and what, if anything, can be done to improve simple models (sections 7.4 and 7.5). There is also an analysis of the risk of overheating in retrofitted dwellings and the need for regulations in this area (section 7.6). Finally, there is a review of the methods used in this study, to lend additional credibility to the findings and to help researchers undertake measurement work in buildings in the future (section 7.7).

7.2 IWI use in Great Britain

It is important to first reflect on the current use of internal wall insulation in Great Britain. National household energy efficiency statistics are regularly produced by BEIS, the Government department that controls policy for retrofitting existing homes. These statistics detail energy efficiency measures installed under the Energy Companies Obligation (Great Britain 2013a) or the Green Deal (Great Britain 2013b): Government-led schemes to promote the installation of energy efficiency measures throughout the UK. Of all the solid walls insulated between January 2013 and March 2017, 95% were fitted with external wall insulation, leaving only 5% fitted with internal wall insulation (BEIS 2018). It is important to note that these statistics only reflect the insulation measures installed under Government schemes. Insulation paid for privately, whether internal or external, will not be included here. It is not possible to estimate the number of homes insulated privately; it is only possible to assess that a small number of solid wall homes are fitted with internal wall insulation.

Judging by Government statistics, IWI seems to be considered an alternative to external wall insulation, rather than a first choice. In a recent report by BEIS (2017a), low IWI take-up was associated with its greater expense, the disruption of installation, and a loss of internal space. This was further discussed in Chapter 2. To help combat some of these issues, the Government has been investigating the use of thin internal wall insulation. A report published in late 2017 shared the results of a model used to assess the energy-saving benefits of thin IWI (BEIS 2017a). Compared to regular IWI it could prove less expensive, less disruptive to install, and could take up less space in the house. It could also reduce the likelihood of certain unintended consequences, such as moisture problems brought about by a change in hydrothermal properties. BEIS is undertaking this investigation and encouraging innovation in this area to help increase uptake of IWI to meet carbon targets (BEIS 2017a; Palmer & Terry 2017).

7.3 Using IWI to reduce energy demand in homes

The thermal performance and energy demand results detailed in this study show that using internal wall insulation can help reduce carbon emissions substantially. Wall U-values were reduced by 88% to 0.21 W/m²K,
achieving the target U-value prescribed in Part L1B of the Building Regulations (DCLG 2016b). The amount of energy saved by installing IWI was found to be 52%; significantly reducing annual gas demand down to 5468 kWh. If installed correctly, internal wall insulation could make older homes more energy efficient, cheaper for their occupants to heat, and warmer for them to live in.

This is, however, dependent on good quality installation. Anecdotal evidence and studies such as that by Forman (2016) show that internal wall insulation, among many other retrofit measures, is not generally installed to a good standard. The necessity of a recent guide, published by BEIS and entitled “Solid Wall Insulation: Best Practice and Innovation” (Palmer & Terry 2017), seems confirmation of this concern. Forman (2016) concludes that if the quality of installation observed in the study is representative of most installations, then it is likely that unintended consequences will occur. Poor installation can be due to a range of different reasons including management, skills and training, and Government policy. For example, ECO policy prompts as much retrofit to be undertaken as possible at the least possible cost. This is not a good way to retrofit to a high standard reducing energy demand, though it is a way to unintentionally create moisture issues.

As discussed in the literature review in Section 2.3.3, a performance gap comes from three primary sources: poor retrofit quality, the inaccuracy of models, or unexpected occupant behaviour. The houses used in this study were insulated correctly, which resulted in a significant reduction in energy demand. There were no occupants to behave unexpectedly. However, there was a difference between measured and modelled values. The U-value reduction measured in this study was better than predicted. The heat transfer coefficient reduction in percentage terms was quite accurate, but in absolute terms the RdSAP model overpredicted the reduction significantly by 63 W/K (66%). This in turn meant that the percentage reduction in energy demand was quite accurate, however in absolute terms the RdSAP model overpredicted the reduction in central heating demand by 2776 kWh, 55%.

This can be put into the context of previous studies that have compared RdSAP models to measurements, reviewed in the literature review in Section 2.3.3. Simple models such as RdSAP often overestimate energy demand in existing homes (Birchall et al. 2011; Gupta & Gregg 2016; Sunikka-Blank & Galvin 2012), as evidenced in this study. Sunikka-Blank & Galvin (2012) defined this as the ‘pre-bound effect’; predicted energy savings cannot be realised in part because homes do not perform as badly as models assume. This aligns with the findings of several previous studies, where energy savings from retrofit were not as significant as predicted (Gupta, Gregg, Passmore, et al. 2015; Hong et al. 2006; Gupta & Gregg 2016; Khoury et al. 2016). The term ‘performance gap’ implies that the insulation performed poorly. In fact, in this study, it performed better than expected. There was a difference between measured and modelled energy demand only because the model is not a good reflection of reality.

7.4 The implications of poorly predicting models

This poses the question; does it matter if there is a difference between model predictions and reality? If a simple model can predict the performance of building elements both before and after insulation, then perhaps
not. For instance, thermal performance could be improved by fitting the maximum amount of insulation possible without causing moisture problems. Whatever energy savings are achieved would be considered good, as they help reduce CO₂ emissions without causing issues with the building. This is an elemental approach to building retrofit; it is similar to the way that the current L1B of the Building Regulations (DCLG 2016b) work. However, ‘helping reduce CO₂ emissions’ is not a measureable target around which to retrofit a house or plan a Government energy efficiency scheme.

To predict cost savings for a consumer, or to measure CO₂ emissions reduction for a Government scheme, a more accurate model is required. Inaccurate models have serious implications. It is widely considered that improving the energy efficiency of solid wall homes could contribute significantly to meeting the UK’s CO₂ emissions targets. Installing insulation could reduce energy demand, however when models similar to SAP are scaled-up to predict absolute savings for building stock, they are likely to over-predict. This issue is not insignificant: part of the Government’s current strategy is to meet carbon budgets is by improving the energy efficiency of existing building stock. If that strategy is to be successful, more accurate models are needed.

There are further implications for energy efficiency schemes due to inaccurate models, such as cost effectiveness for a single house. RdSAP assessments are used to calculate the current energy efficiency of a building and the amount of energy that could be saved by implementing retrofits. Both of these are displayed on Energy Performance Certificates (EPCs) to help householders estimate energy costs. RdSAP is arguably the primary decision-making tool for householders deciding whether or not to install solid wall insulation. In this study, RdSAP was able to predict energy saving as a percentage, but not in absolute terms. If householders were told their energy bills would be reduced by 57% through installing IWI, as RdSAP predicted in this case, but in reality saved only 52%, the small discrepancy may go unnoticed, or could be explained away by the occupants’ use of the house. However, EPCs do not express the amount of energy likely to be saved as a percentage, but as a monetary value. Using the British Gas Standard Gas Tariff (including VAT on 19/06/2017) of 3.71p/kWh, it has been calculated that £217 would be saved in an average year. RdSAP predicts a saving of £339 (Table 7-1). The performance gap between measured and actual savings was included in the Green Deal energy calculations as three reduction factors, which add up to a reduction in performance of 49% (DECC 2014b). This appears to be acknowledgement from the UK Government that predicted RdSAP savings cannot be achieved. If that is known, it is false advertising to list exact cost savings on EPCs, rather than percentage savings or other benefits.
Table 7-1: Differences in measured and modelled energy demand

<table>
<thead>
<tr>
<th></th>
<th>Yearly saving due to IW1 Measured</th>
<th>Improved RdSAP</th>
<th>Difference between measured and improved RdSAP</th>
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</thead>
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<tr>
<td>Central Heating Consumption (kWh)</td>
<td>5030</td>
<td>7865</td>
<td>2835</td>
</tr>
<tr>
<td>Gas Consumption at 86% boiler efficiency (kWh)</td>
<td>5852</td>
<td>9145</td>
<td>3293</td>
</tr>
<tr>
<td>Cost at 3.71 p/kWh British Gas standard tariff (£)</td>
<td>217</td>
<td>339</td>
<td>122</td>
</tr>
</tbody>
</table>

7.5 Predicting energy savings from retrofit accurately

It is necessary to plan carbon budgets, predict the effectiveness of energy efficiency schemes, and inform consumers of what they are purchasing. These are all good reasons to create accurate models. There are alternatives to steady-state models such as RdSAP that can predict energy demand much more accurately. Dynamic thermal models could be used by Government to plan energy efficiency schemes to meet carbon budgets. However, on a single house, although the calculation method may be more sophisticated, the models would still suffer from the poor quality of input data that RdSAP models do currently. Dynamic thermal models are also time-consuming and complex to produce, so would be impractical to use before a wall insulation retrofit on a single house.

RdSAP, the current National Calculation Methodology, is the quick, low-cost method used to easily assess the energy demand of homes. To predict energy demand more accurately, a new National Calculation Methodology could be created; for this there are the following options:

- Improve the inputs to or calculations in RdSAP; or
- measure current thermal performance in homes before retrofit, and predict post-retrofit energy demand with either:
  - an RdSAP model ‘calibrated’ with measured values; or
  - a statistical model.

In Chapter 4, the work shows that RdSAP overpredicted air permeability and heat transfer coefficients (HTCs), and that the standard assumed U-values are too high. Chapter 5 showed that RdSAP also overpredicted energy demand both before and after retrofit. To improve the HTCs produced by RdSAP, the model could better calculate infiltration and the wall U-value tables could be updated\(^1\). However, upon enacting these changes, the ‘improved RdSAP’ models still could not calculate accurate HTCs. The RdSAP models were further interrogated to discover reasons for this.

\(^1\) An update: since the submission of this thesis, the U-value tables for RdSAP have been updated and U-values for solid walls changed from 2.1 W/m\(^2\)K to 1.7 W/m\(^2\)K, aligning to the field of evidence shown in the literature review.
The HTC of the left house without insulation was overpredicted by 25%, whereas the HTC of the left house with IWI was predicted accurately. The inaccuracy in the uninsulated HTC may have been caused by inaccurate U-values of other elements taken from tables. HTCs calculated using ‘improved RdSAP’ were compared to measured HTCs in Section 4.5.1. By reducing any of the values in the model, for example the floor U-value, both calculations were affected: the predicted HTC for the uninsulated house was improved, but the prediction for the house with IWI was worsened.

Another reason the prediction of the uninsulated HTC was inaccurate in the house with IWI is the effect of thermal bridging (see Appendix 1). Thermal bridging is calculated by multiplying the internal surface area of the building by 0.15, then adding this to the fabric and infiltration HTCs to produce the total calculated HTC. This results in almost exactly the same value for thermal bridging before and after insulation. The house with internal wall insulation had many more thermal bridges, in particular the party wall and the floor of the upper story, both of which penetrated through the IWI to the outside. It is likely the combined effect of inaccurate U-values and incorrect thermal bridging factors that resulted in inaccurate HTCs. To discover the source of inaccuracies and improve the inputs to and calculations in the model, it will be necessary to collect more detailed comparisons of measured buildings against RdSAP models.

Instead of changing these parts of RdSAP it could be better to measure the performance of buildings in their original state to help predict energy saved by a retrofit measure. As shown above, measuring individual U-values and combining them into a HTC can result in inaccuracies. Therefore, measuring the final HTC would be necessary. The predominant method for measuring HTCs is the co-heating test. The co-heating test requires elevated temperatures and steady internal conditions, making it impractical for wide scale use in occupied buildings. Other methods, such as the primary and secondary terms analysis and re-normalization (PSTAR) and quick U-value of buildings (QUB) methods, are also available (Mangematin et al. 2012; Palmer et al. 2011); these take less time, but would still be intrusive to occupants.

An alternative could be to add temperature sensors to smart meters in order to calculate HTCs. Currently, there is no proven method for this, but the work is already being undertaken through the International Energy Agency’s Energy in Buildings and Communities Programme (IEA-EBC 2018). The intention is that dynamic data analysis techniques could produce measures of thermal performance from optimised measurements. Any measurements of temperature and energy demand are challenging to convert into HTCs because they include the effect of occupant behaviour. However, starting from known values would better predict energy savings from retrofit. This method would still need to be used in conjunction with a simple building model, which could be ‘calibrated’ against the measured smart meter performance, to suggest retrofit strategies and predict energy savings. These predicted energy savings could be tailored to the occupants’ current energy demand. They could also incorporate the take-back effects likely from the increase in indoor temperature after retrofit. This could produce very accurate predictions for the consumer.

‘Improved RdSAP’ models can be made using the RdSAP model with measured data. In this study the ‘improved RdSAP’ models, with accurate inputs of U-values and air permeability, predicted energy demand
more accurately than the ‘typical RdSAP’ models. This was also shown in previous studies by Birchall et al. (2011), Stevens and Bradford (2013) and Chambers et al. (2015). Using a measured HTC yields even better results, Table 7-2. Here a hybrid HTC-RdSAP model has been used to successfully predict energy demand after retrofit, within 2% of the measured value. The HTC-RdSAP model was produced using the measured HTC in RdSAP to calculate energy demand in the existing house. The energy demand prediction in the retrofitted house was produced using measured airtightness and U-values. However, these do not need to be measured, and could be included in an improved calculation method. It appears possible that simple models, when used with measured data, can predict energy savings from retrofit very accurately. This would be the basis of a smart meter prediction of energy saving.

Table 7-2: Predicted energy demand pre and post retrofit using measured HTCs

<table>
<thead>
<tr>
<th>Insulation state</th>
<th>Measured</th>
<th>Modelled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Extrapolated using linear regression</td>
<td>Typical RdSAP model</td>
</tr>
<tr>
<td></td>
<td>Annual central heating demand (kWh)</td>
<td>Annual central heating demand (kWh)</td>
</tr>
<tr>
<td>Uninsulated</td>
<td>9735</td>
<td>16187</td>
</tr>
<tr>
<td>IWl</td>
<td>4703</td>
<td>8379</td>
</tr>
<tr>
<td>Reduction in left house</td>
<td>5032 (52%)</td>
<td>7808 (48%)</td>
</tr>
</tbody>
</table>

<sup>a</sup>The model uses a measured HTC in the model of uninsulated house, and uses accurate wall U-values and air permeabilities in the model of the house with IWl.

Until either RdSAP can be improved or measuring thermal performance becomes more commonplace, it may be more appropriate to stop modelling homes with the current technique, as the evidence shows that it can produce false estimates. Instead, when retrofitting an element the focus should remain on the best performance for that particular element. Energy efficiency schemes could be planned and evaluated using measured data of the housing stock rather than modelled information from RdSAP. This could be done using the National Energy Efficiency Data-Framework (NEED) (Formatting Citation), which matches gas demand data to energy efficiency data at the house scale. Probabilistic statistical models could be produced from the NEED and used to predict the range of likely energy savings from retrofit on a house. Models can never predict completely accurately, predicting a range of likely outcomes based on measured data from past installations is more reasonable than predicting a single value using a deterministic model. Consumers could then be
provided with a range of likely cost savings from energy efficiency measures. This data-driven approach could reduce the need for models until those models can be improved and verified for use at a single building scale.

7.6 Preventing overheating in retrofitted homes

In the case studied and presented in this thesis, overheating risk was not considered a barrier to retrofitting houses with internal wall insulation. Overheating would be infrequent and moderate. This is true in the current climate and will remain true until around the 2060s, based on climate predictions. Past this date, mitigation strategies would be needed in homes similar to these with IWI because overheating would become more frequent and more severe.

To allow occupants to enjoy constant comfort in a similar house, even during periods of unusually high outdoor temperature, a mitigation strategy would be needed. A mitigation strategy would also likely be needed for houses in warmer parts of the country or those that had further energy efficiency measures installed, such as floor insulation. The use of a mitigation strategy is dependent on occupants being well informed, and able and willing to implement the strategy. People in temperate climates across the UK are not used to experiencing warmer weather and do not always know how to act. This is worsened by the occurrence of brief hot spells rather than long periods of hot weather. People generally do not learn to change their behaviour or adapt. It is possible to open windows at the right times or use blinds for shading, but this mitigation strategy would require people to learn and become accustomed to new habits. For example, it is commonly held that opening a window on a hot day can increase comfort indoors. However, opening windows when it is warmer outside than inside further exacerbates overheating. Humans are poor thermometers, and it is not always easy to judge which is the warmer temperature. Without proper information and learning, overheating mitigation strategies that are fully under the control of occupants are unlikely to take significant effect.

A proportion of the population will also have mobility issues that prevent them from opening windows or closing blinds. Further to this, older individuals in particular have a reduced ability to sense heat, so may not notice when it is very hot and will therefore not act to reduce the heat. General willingness is also in question; occupants may not want to have their blinds closed in the day as it prevents natural light from entering the house. They may also feel that opening their windows at night is a security risk or will expose them to noise, smells, insects, pollen, or air pollution. These are all serious barriers to the use of mitigation strategies, which may result in a lack of uptake in the general population.

To regulate indoor temperatures while addressing these barriers to action, it could be possible to install inbuilt mitigation features when installing IWI in houses. This idea is supported by a Government report, insisting that installing mitigation with retrofit measures is necessary (DCLG 2012). A holistic view of whole house retrofit by industry could be a successful means to prevent overheating. Mitigation of solar gains could be achieved through the installation of brise soleil or awnings: used widely throughout Europe, they restrict direct solar heating while allowing natural light into rooms. Concerns around opening windows due to pollen or insects
could be removed by installing screening to windows. If noise or pollution is the problem, specialised wall vents could be fitted with baffling or filters. The measures used should be both issue and location specific. If installed as part of a package at the time of IWI rather than individually at a later date, these measures should also prove more cost effective.

Crucially, this whole-house retrofit approach would prevent indoor temperatures from rising, which is key to the UK’s efforts to reduce CO₂ emissions. If indoor temperatures continue to rise after improper installation or due to an inability or unwillingness to implement mitigation strategies, homeowners may blame IWI as a whole. It could come to be associated with higher indoor temperatures, and its low uptake could be further impacted. There is also a danger that homeowners may try alternatives such as air conditioning, which regulates indoor temperature but has a negative long-term impact on carbon emissions. It is widely understood that once occupants have air-conditioning, they use it frequently to create a year-round homogenous indoor temperature. The CO₂ emissions associated with electricity use are falling all the time, but are still at around three times that of gas use; therefore, emission savings from insulation could be reduced by the introduction of air conditioning units through the country.

To stimulate the building industry to undertake whole-house holistic retrofits, overheating must be legislated for in the Building Regulations (2010). Overheating is already a wide spread issue in new homes and so far industry has not prevented it willingly. The prevention of overheating is not currently required in any building; solar gains are reduced in new homes through Part L of the Building Regulations (DCLG 2013a), but even this basic protection is missing for existing homes undergoing thermal retrofit. Robust rules in building regulations may be required to drive overheating mitigation adoption. With low housing demolition rates, internal wall insulation must be expected to stay in place for over 40 years after installation. Under a changing climate, without a robust mitigation strategy, IWI will increasingly pose an overheating risk in houses similar to those measured in this study.

If overheating in existing dwellings were to be regulated for, a method would be required. Currently SAP has a method in Appendix P: Assessment of internal temperature in summer; although this is not used for overheating in Building Regulations, but for limiting air conditioning use. It is widely accepted in industry and evidenced in some research (Morgan et al. 2017), however, that steady-state calculation methods such as SAP are inappropriate for calculating indoor temperatures for the purposes of overheating. Dynamic thermal simulation could be used instead. However, as previously discussed, this would likely be too burdensome for someone undertaking thermal retrofit of a single house.

A more appropriate tool may be a checklist to be completed when retrofitting a house. The checklist would be based on known characteristics, or a combination of characteristics known to cause overheating. This is a risk assessment method, and would be similar to that included in the Housing Health and Safety Rating System (HHSRS) (ODPM 2006). This new risk assessment could be used to identify overheating risks before upgrading a home. It could include a list of known overheating risk factors, weighted by severity of influence, and allow for when it is impractical for an occupant to open windows for reasons of security, noise or pollution. The
assessment could offer design solutions that are location-specific, and simple for occupants to use. An overheating risk assessment for existing homes, as well as newly built ones, could be included in the national building regulations as we move towards a warmer future.

7.7 Study review

Finally, the study and the methods employed in this research are reviewed. This study used a pair of highly instrumented test houses that had their thermal performance, energy demand, and overheating risk measured both before and after retrofit of internal wall insulation.

The sole use of a pair of unoccupied test houses meant that there were few limitations on the type of tests that could be done or on the timing of said tests. Tests such as infrared thermography and the blower door tests to measure air tightness could be done on days with ideal weather conditions, and not when it was convenient for an occupant. When measuring U-values, heat flux plates were bonded to wall surfaces with heat flux paste, and wires were attached to the walls with nails; ruining wall finishes would not be acceptable in an occupied house. Lastly, co-heating tests could be used to measure thermal performance, which is not possible in occupied houses due to the elevated temperature and time required, and the fact that occupancy would affect the results.

While collecting energy demand and temperature data, the houses were equipped with many sensors. For example, the living rooms and bedrooms had 24 thermocouples attached to the walls, an operative temperature station, a central air temperature sensor and U-value measurement equipment. It was possible to use both the number and the type of equipment because the houses were unoccupied. In an occupied house, this would have been unacceptable to most occupants. Sensors were placed in the volumetric centre of rooms or in the place of furniture, which is not always possible in a house that is furnished and being used. The measurements were also taken over a long period of time: for this project, 8 months. Some building measurement studies are longer but fewer sensors tend to be used. In this case, the most suitable measurements were taken, yielding high quality data that allowed assessment of the thermal performance, energy demand and overheating risk of the houses.

Regression was used for the analysis of both the winter energy data and the summer operative temperature data. Testing each predictive variable alone and with other variables was an effective strategy for finding the predictive variable(s) with the best relationship with either energy data or summer operative temperature data. The exponentially weighted outdoor running mean temperature ($T_{\text{wos}}$) was found to have the best relationship with summer operative temperature, as in the work of Oraioopoulos et al. (2017). $T_{\text{wos}}$ was also found to have the best relationship with heat demand as tested for the first time in this study. This was thought to be effective because it incorporates some of the complexity of a dynamic model into a simple model by including the outdoor air temperature of both today and previous days. This use of previous days’ temperature data is a way of incorporating the effect of thermal mass and of thermal insulation into the models without doing so explicitly. Interestingly, incorporating solar radiation in the models did not improve
them notably. Presumably this is because solar is already inimplicitly included when using outdoor temperature as they are correlated with one another: more solar radiation causes higher outdoor temperatures. The simple models used here are an important contribution to knowledge; they could be used by future researchers to normalise data collected in buildings.

The Degree-Days method was tested as a method of predicting energy demand in the houses. The most accurate form of the model was built: a daily model. However, through splitting the data and testing the method, it was revealed that it did not offer accurate predictions in this situation. In most scenarios where the Degree-Days method is used there is no opportunity for data-splitting and model checking; therefore it may be being used in good faith but providing inaccurate estimates of building energy demand. This is an important finding, and future work is required to understand better the limitations of the Degree-Days method and validate it against measured data.

Measurements taken in one house fitted with IWI answers detailed questions on the energy demand and overheating in that house. The results can be extrapolated to other houses of the same type, in suburban locations and with the same features, such as cross ventilation. This study does not offer guidance for the installation of IWI in houses of other types; particularly flats, houses with single aspect ventilation, or in urban heat islands, which are already known to be indicators of risk for overheating. Analysis of the 2015 English Housing Survey data reveals that, of the 23.5 million dwellings in the England, 6.2 million have solid walls, and 21% of those solid wall dwellings are semi-detached (DCLG, 2017a). The results here may be applicable to many semi-detached dwellings and may also be representative of end-terrace properties, which constitute a further 11% of solid wall dwellings (DCLG, 2017a). The test houses were south-southeast facing; west facing homes could be at a greater risk of overheating due to high solar gains from low evening sun. Further work is therefore required to understand how other types of houses would perform, in particular mid-terrace houses with solid walls (which constitute 30% of solid wall dwellings in England) and flats with solid walls (which constitute 26% of solid wall dwellings in England) (DCLG, 2017a).

7.8 Summary

Internal wall insulation significantly reduces the energy demand in a house. Its installation through energy efficiency schemes could contribute to the reduction of UK carbon emissions. Despite this, it is used infrequently in Great Britain, making up less than 5% of solid wall insulation installations. This indicates that it is likely a second choice to external wall insulation. There is some evidence that Government is interested in increasing the proliferation of IWI to meet carbon reduction targets.

There is a performance gap identified between the real reduction in energy demand due to IWI and the reduction predicted using RdSAP. This could have serious implications for the UK; it could prevent the country from meeting CO₂ reduction targets, reduce the cost effectiveness of energy efficiency schemes and increase payback times for retrofit measures. RdSAP cannot reliably predict energy demand in solid wall buildings due
to flawed calculations within the model. Either the model must be improved, alternatives using measured data created, or models should not be relied on to predict energy savings.

Increased indoor temperatures caused by IWI can be prevented through a simple mitigation strategy. However, to implement such strategies, occupants must be able, willing, and well-informed. To help homes stay cool, a whole-house retrofit approach could be implemented, whereby mitigation measures are installed along with IWI. To stimulate this whole-house approach, overheating would need to be better legislated for in building regulations. Simple methods to predict overheating would also need to be developed.

The methods used to assess the effect of IWI on thermal performance, energy demand and overheating were successful. Internal wall insulation improved the thermal performance of the solid wall houses and in turn this significantly reduced energy demand. These findings are applicable to the 32% of the solid wall housing stock that are semi-detached or end-terrace. However, more investigation is needed into the energy savings of other archetypes.
8 Conclusions

8.1 Background and research design

The UK housing stock is one of the oldest in Europe. The stock is energy inefficient because many of its oldest homes have solid walls, which exhibit a high rate of heat loss. Reducing this heat loss would help to improve the energy efficiency of solid wall homes, which is part of a least-cost plan to reduce CO₂ emissions in the UK. Solid walls can be insulated with internal wall insulation (IWI), which has the benefit of being able to be installed in many listed and heritage buildings. Prior to this thesis, the potential of IWI to improve thermal performance and reduce energy demand of solid wall buildings was not well quantified. There was also a concern that IWI could cause summer overheating in UK solid wall dwellings. Overheating not only causes occupants discomfort, but can also lead to serious health problems. Several modelling studies have shown that summer overheating is likely in dwellings with IWI, but there was very little empirical evidence prior to this thesis.

The aim of the research was to quantify the impact of retrofitted internal wall insulation on thermal performance, energy demand and summer overheating in UK solid wall dwellings; this has been achieved. The intent was also to give confidence in estimating the amount of energy demand reduction that can be achieved when retrofitting the UK solid wall housing stock; recommendations have been made in the discussion to achieve better predictions in the future. Further, the research was to offer knowledge on the summer overheating potential and recommendations for providing comfortable summer living environments for occupants in houses with IWI; which have been provided.

Two semi-detached solid wall dwellings were used as a test facility in which to investigate internal wall insulation and its impacts. The uninsulated houses had their thermal performance characterised, then one house was fitted with internal wall insulation. Thermal performance tests were repeated on this house, which quantified the reduction in air permeability, U-values and whole house heat transfer coefficient due to IWI. The energy demand of both houses was quantified and compared pre and post IWI installation. Measures of thermal performance and energy demand were compared to RdSAP models to identify any possible performance gap. Overheating risk was also assessed pre and post IWI installation, and a simple overheating mitigation strategy tested the prevention of high indoor temperatures. The key findings with regards to houses with retrofitted IWI; predicting thermal performance and energy demand; and the methods used are summarised below.

8.2 Retrofitted IWI Key findings

By investigating the impact of retrofitted internal wall insulation on thermal performance, energy demand, and summer overheating in UK solid wall dwellings, a number of key findings were established:
The retrofit of IWI in these houses reduced the point U-values of the solid walls by 88% from 1.72 W/m²K to 0.21 W/m²K; a very significant reduction. The walls with IWI had lower U-values than the 0.3 W/m²K limiting value for the walls of new build dwellings (DCLG 2016a). Internal wall insulation is very effective at reducing wall U-values and its use should be recommended when retrofitting solid wall homes.

The whole house heat transfer coefficient of the house fitted with IWI was reduced by 39%, from 245 W/K to 149 W/K. This led to significant savings in energy demand. The measured energy demand data were extrapolated into yearly energy demand both before and after IWI was installed using a Test Reference Year of weather data. Yearly gas consumption was reduced by 52% by installing IWI. This is a significant saving, as the retrofit of IWI on solid wall buildings could make them cheaper for occupants to heat, more comfortable for occupants to live in, more energy efficient and contribute to meeting carbon budgets in the UK.

A side-by-side comparison of a house with and without internal wall insulation showed that, in summer, IWI increased indoor operative temperature. Overheating was found to occur during periods of unusually hot weather. However, under current climate conditions, overheating in houses of this type with IWI would occur infrequently. Overheating risk should therefore not be considered a barrier to the uptake of IWI.

Future weather data were used to predict indoor operative temperatures in a warming climate. This data showed that, under a medium-emissions scenario, houses fitted with IWI would overheat infrequently until 2066. However, from 2066 onwards, these houses would be prone to regular overheating.

An overheating mitigation strategy was tested in the houses, it included the use of blinds for solar shading and open windows at night to purge warm air. The mitigation strategy reduced indoor temperatures in houses fitted with IWI. It also reduced overheating risk, and would provide comfort in houses fitted with IWI into the 2090s. This strategy resulted in equal bedroom temperatures in both the house with and without IWI, demonstrating that IWI does not need to effect night-time comfort.

These findings are broadly applicable to other houses with similar characteristics. This includes the 32% of the English solid wall stock that is either semi-detached or an end-of-terrace house. However, these findings should not be assumed to apply to dwellings of different archetypes, those without cross-ventilation, or those in urban heat islands. It is likely that houses in warmer locations such as the south coast of England and London would have a higher current and future overheating risk.
8.3 Predicting thermal performance and energy demand key findings

It is important to be able to accurately predict the improvement in thermal performance and the reduction in energy demand due to energy efficient retrofit. If accurate predictions are not made it can result in a performance gap: a larger energy saving will be predicted than is possible. The findings from this research relate mainly to RdSAP, the UK government’s current method for predicting the energy performance of existing homes. The following are the key findings:

In the uninsulated houses, RdSAP overestimated the combined air infiltration and ventilation rate by up to 83%, the tabulated U-values were around 17% higher than measured and it overestimated the heat transfer coefficient by up to 49%. RdSAP did not calculate the thermal performance characteristics of the uninsulated houses accurately.

In the house with IWI, RdSAP overestimated the combined air infiltration and ventilation rate by 85%, the tabulated U-values were 186% higher than measured and it overestimated the heat transfer coefficient by 35%. RdSAP did not calculate the thermal performance characteristics of the house with IWI accurately.

The inaccuracies of these thermal performance measures affected the RdSAP models’ ability to accurately predict energy demand. RdSAP overpredicted gas consumption by 66% before IWI, and by 78% after IWI was installed. The combined effect of this was that RdSAP overpredicted energy saving by 55%; this is the performance gap.

Improved RdSAP models were produced, using measured U-values and air permeabilities in the models instead of tabulated or calculated values. These improved the models’ predicted energy demand more accurately, reducing the difference between measurement and prediction in the uninsulated house from 66% to 43%, and in the house with IWI from 78% to 29%. This also reduced the performance gap but it was still quite large.

When calculating U-values, the BS EN ISO 6946:2007 (BSI 2007c) calculation method and guidance produced accurate predictions of the solid wall, but inaccurate predictions of the wall U-value when IWI was installed. The method and guidance needs improvement.

RdSAP should not be used to predict the magnitude of energy savings due to retrofit. The recommended measures presented on EPCs and their related cost savings should be treated with caution. Recently, RdSAP has been improved by updating the assumed U-value for solid walls to 1.7 W/m²K, however there are still several areas that need further improvement. These improvements include the calculation of infiltration and ventilation rates, the use of the same thermal bridging factor for all constructions. The calculations of RdSAP should also be reviewed, and validated against measurements collected in test houses; this may be useful future work that would improve the method.
8.4 Methodology Key Findings

The purpose of this work was to investigate IWI; during this investigation many methods were used. Some methods were novel in this thesis and could be used by other researchers. These are the key findings:

The use of a highly instrumented pair of unoccupied test houses was a very effective way of investigating IWI. It allowed a direct comparison of energy demand and indoor temperature when one had IWI and the other was uninsulated. It also allowed co-heating tests to be performed, which cannot be done in occupied houses. Data from the co-heating tests was used to calculate the heat transfer coefficients. This data collected was invaluable in the assessment of IWI and on the accuracy of the predictions from RdSAP.

Linear regression was used to extrapolate energy demand data into a year of energy savings due to IWI. Linear regression was also used to assess the effect of the mitigation strategy in the house with IWI. The exponentially weighted outdoor running mean temperature was used successfully as an independent variable in models of both energy demand and indoor temperature. Linear regression models with this predictor could be used by future researchers to compare data from different time periods without the need for complex time series analysis.

The degree-days method was also tested as a tool for normalising and extrapolating energy data. However, it was shown in this case to be inaccurate. This could be a concern considering its use in industry, where data-splitting and validation is not possible. This could be investigated in future work.

8.5 Contributions to knowledge

The work from this thesis has provided a number of contributions to knowledge:

Prior to this thesis, there was little measured evidence that allowed for a systematic review of the effect of IWI. In particular, few studies measured houses both before and after retrofit, there were several studies that measured only after retrofit and many studies that instead relied on models. There was only one study by Stevens and Bradford (2013) that measured pre-post IWI air tightness, U-values and energy demand of English brick houses, however these measurements were not all taken in the same houses. There were no studies of houses with IWI that measured heat transfer coefficients. There was only one study, by Makrodimitri (2010), that measured summer indoor temperatures in houses with IWI and none that assessed overheating using adaptive criteria.

In this study, it was found that the installation of internal wall insulation improved thermal performance, significantly decreased energy demand, only slightly increased indoor temperature, and any overheating risk could be simply mitigated. The measurements and analysis of this thesis should give confidence in the use of IWI, and its ability to reduce energy demand and CO₂ emissions in UK housing stock, while maintaining
comfortable summer conditions. Further measurement work is required in dwellings of different types and dwellings without cross-ventilation.

RdSAP has been found capable of predicting the percentage of energy saved due to IWI, but it is unable to predict the magnitude of energy savings accurately. The research has shown that while some inputs to the model were inaccurate, such as those for solid wall U-values, the calculations in the model itself created further inaccuracy. RdSAP would need to be improved before it could be used to calculate fuel and cost savings as an accurate retrofit design tool.

8.6 Recommendations to stakeholders

Most of the recommendations are to the UK Government because they create energy efficiency retrofit schemes, commission the National Calculation Methodology: RdSAP and develop building regulations. Other recommendations are for industry, academia and the general population.

Recommendations to Government:

Government should encourage the use of IWI more actively through energy efficiency schemes. At present, IWI is installed infrequently and appears to be used only as an alternative to EWI. IWI is cheaper than EWI to install, its thermal performance is very good and it therefore saves significant amounts of energy, over 50% in this study. In the context of energy efficiency schemes, which are often aimed at people in fuel poverty, IWI could make homes cheaper and warmer to live in.

Government should not use simple building models when planning energy efficiency schemes. As shown in this study and several others, RdSAP overestimates energy savings. Using simple models with uncertain inputs to plan energy efficiency schemes would result in an overestimate of energy savings at stock level. Energy efficiency schemes would therefore not contribute as expected towards reducing national energy demand and meeting carbon budgets. As alternatives, government should use measured thermal performance data within simple models to produce stock models, or create statistical stock models based on measured energy efficiency schemes.

Government should remove the energy cost savings from retrofit included on Energy Performance Certificates. RdSAP cannot produce accurate calculations of energy savings from retrofit. Reduction factors were included when calculating Green Deal energy savings, clearly Government is aware that RdSAP does not produce accurate predictions. Continuing to include cost savings on Energy Performance Certificates is false advertising.

There is much scope for improving simple models, which could be done by industry or academia, but ultimately need to be accepted by Government. At a single house level, simple models must be able to predict energy savings from retrofit to predict cost savings for the consumer. It is this saving of money on energy bills that encourages homeowners to retrofit.
Government should verify the energy savings from houses retrofitted as part of energy efficiency schemes. Although currently impractical with co-heating tests, this could be done in the future by measuring the pre-post heat transfer coefficients using smart meters with temperature sensors. There could be a penalty for retrofit installers whose work does not perform as designed, encouraging industry to close the retrofit performance gap.

Government should regulate for overheating in buildings that have been retrofitted with energy efficiency measures. There is an overheating problem in many new build properties that could also occur in retrofitted homes if they are made highly energy efficient. Industry has not yet tackled the issue, despite potential reputational damage; therefore it falls to government to act.

Government should enable a culture shift in society by informing people about how to keep their homes cool. Currently many people are ill informed on how to prevent overheating in their homes; the focus in British culture has in the past been keeping homes warm. To encourage this cultural shift, public health warnings are needed. These already occur and are included in the Heatwave Plan for England; however, these are centred around health warnings such as drinking enough water, the warnings could include methods for keeping your house cool to help educate the public.

Recommendations to academia:

The use of simple models such as RdSAP to predict energy demand may never be accurate enough and alternative methods need to be developed. Academia are already developing models, these should be produced with simplicity and cost in mind for use at the single house scale. The discussion recommended two options. The first option is to make predictions using a simple model that includes a measured heat transfer coefficient, possibly produced using data from smart meters. The second option is to use statistical models using known relationships between retrofit measure and energy demand reduction.

The results produced from this study should encourage the use of the research methods. A range of different measurement strategies should be used when investigating buildings, these should include large stock studies, smaller sets of occupied case studies and systematic reviews using synthetically occupied test houses.

Recommendations to industry:

The retrofit industry must improve the quality of retrofit to ensure problems such as moisture do not occur when using IWI. The retrofit industry should become more highly skilled and more aware of unintended consequences. If houses are retrofitted poorly, unintended consequences could occur, which would damage the reputation of the entire retrofit industry. Reputational damage has already impacted the cavity wall insulation industry. If other retrofit measures, such as IWI, gain negative
reputations property owners may refuse to have them installed which would make it difficult for the UK to meet carbon reduction targets.

The retrofit industry should market internal wall insulation more at homes that are listed or in conservation areas. One of the particular benefits of IWI is that it doesn't change the outside appearance of a building. This means that even these older protected buildings can be made more energy efficient, if done carefully to prevent issues with moisture.

The retrofit industry should retrofit houses holistically, where suitable passive mitigation strategies are fitted at the same time as insulation. Industry should be responsible for unintended consequences such as overheating and recommend the installation of mitigation methods at the time of energy efficiency works.

To prevent the rise of air conditioning, industry must innovate new overheating mitigation techniques that are acceptable to the public and sympathetic to current housing design. Innovation should be in the areas of passive mitigation including secure and noise attenuating ventilation and visually appealing external shading.

8.7 Summary conclusion

The impact of internal wall insulation on thermal performance, energy demand, and overheating was measured using a pair of unoccupied solid wall test houses. IWI was installed in one house of the pair, allowing for a comparison between a house with and without IWI. Thermal performance was improved in the house fitted with IWI, reducing wall U-values from 1.72 to 0.21 W/m²K and the heat transfer coefficient by 39%. Energy demand data were collected and extrapolated using a linear regression model and a Test Reference Year of weather data; it was found that IWI decreased energy demand by 52% in an average year. Internal wall insulation should be recommended for use by Government in energy efficiency schemes and by industry more generally. IWI could reduce the energy demand of the existing solid wall housing stock, reducing CO₂ emissions and contributing to meeting national carbon reduction targets.

Indoor temperature data were collected in summer. IWI increased indoor temperatures, however under the current climate these houses would rarely overheat. Future weather data were used to determine that the houses would overheat regularly from the year 2066 onwards. However, overheating was preventable through the use of a simple mitigation strategy consisting of night ventilation and solar shading; the house with IWI would then offer comfortable temperatures into the 2090s. Hot weather events, though currently rare, would cause overheating in houses such as these without a suitable mitigation strategy. However, given the significant energy savings in winter, and the minimal effort required to maintain an overheating mitigation strategy in summer, the installation of IWI is a viable solution for reducing CO₂ emissions from many solid wall homes.
References


Byrne, A., Byrne, G., O’Donnell, G. & Robinson, A., 2016. Case studies of cavity and external wall insulation


Local Government. Available at:


DCLG, 2016e. *Housing supply; net additional dwellings, England: 2015-16*, London: Department for Communities and Local Government. Available at:


DECC, 2016a. *National Energy Efficiency Data-Framework. Summary of analysis using the National Energy Efficiency Data-Framework (NEED)*, Available at:


Historic England, 2017. Listed Buildings [online], Available at:


HM Government, The Building Regulations 2010, Available at:


Hulme, J. & Doran, S., 2014. BRE Report: In-situ measurements of wall U-values in English housing, Watford:


Kreider, J., 2010. Heating and Cooling of Buildings: Design for Efficiency,


Rhee-Duverne, S. & Baker, P., 2013. Research into the thermal performance of traditional brick walls,


Schnieders, J., 2005. *Innendämmung – Potenziale und Grenzen; Protokollband 32, Faktor 4 auch bei sensiblen Altbauten: Passivhauskomponenten + Innendämmung*,

Shrubsole, C., Macmillan, a., Davies, M. & May, N., 2014. 100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock. *Indoor and Built Environment*, 23(3).


White, J.A., 2014. An investigation into the parameters that contribute to the gap between the designed and as-built thermal performance of British housing (PhD. University of Nottingham. Available at: http://eprints.nottingham.ac.uk/14408/2/JW_PhD_Thesis_version_2.pdf [Accessed April 22, 2018].


Appendix 1

SAP WORKSHEET (Version 9.92)

1. Overall dwelling dimensions

<table>
<thead>
<tr>
<th>Area (m²)</th>
<th>Average storey height (m)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.102 (1a) x 2.54 (2a)</td>
<td>= 81.540 (3a)</td>
<td></td>
</tr>
<tr>
<td>8.398 (1b) x 2.38 (2b)</td>
<td>= 19.987 (3b)</td>
<td></td>
</tr>
<tr>
<td>32.50 (1c) x 2.867 (2c)</td>
<td>= 93.348 (3c)</td>
<td></td>
</tr>
<tr>
<td>8.844 (1d) x 2.694 (2d)</td>
<td>= 23.826 (3d)</td>
<td></td>
</tr>
<tr>
<td>1 (1n) x</td>
<td>= 3 (3n)</td>
<td></td>
</tr>
</tbody>
</table>

Total floor area TFA

Σ (1a)…(1n) = 81.904 (4)

Dwelling Overall

Σ (3a)…(3n) = 218.702 (5)

2. Ventilation rate

<table>
<thead>
<tr>
<th>Number of chimneys</th>
<th>main heating</th>
<th>secondary</th>
<th>other</th>
<th>total</th>
<th>m³ per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>

Number of open flues

+ 2 + 2 = 2 x 20 = 40 (6b)

Number of intermittent fans

x 10 = (7a)

Number of passive vents

x 10 = (7b)

Number of flueless gas fires

x 40 = (7c)

Air changes per hour

Infiltration due to chimneys, fans, PSVs

(6a) + (6b) + (7a) + (7b) + (7c) = 40 + (5) = 0.183 (8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (n₁)

2 (9)

Additional infiltration

[(9) - 1] x 0.1 = 0.10 (10)

Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction

0.35 (11)

If both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0

0.07 (12)

If no draught lobby, enter 0.05, else enter 0

0.05 (13)

Percentage of windows and doors draught stripped

100 % (14)

Window infiltration

0.25 x [0.2 x (14) + 100] = 0.050 (15)

Infiltration rate

(8) + (10) + (11) + (12) + (13) + (15) = 0.803 (16)

Air permeability value, q50, expressed in cubic metres per hour per square metre of envelope area

(17)

If based on air permeability value, then (18) = [17] + (8), otherwise (18) = (16)

Air permeability value applies if a pressurisation test has been done or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered

3 (19)

Shelter factor

(20) = 1 - [0.075 x (19)] = 0.775 (20)

Infiltration rate incorporating shelter factor

(21) = (18) x (20) = 0.622 (21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table U2

<table>
<thead>
<tr>
<th>(22)ₐₙ</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>5</td>
<td>4.9</td>
<td>4.4</td>
<td>4.3</td>
<td>3.8</td>
<td>3.8</td>
<td>3.7</td>
<td>4</td>
<td>4.3</td>
<td>4.5</td>
<td>4.7</td>
<td></td>
</tr>
</tbody>
</table>

Wind Factor

(22a)ₐₙ = (22)ₐₙ + (22a)ₐₙ = 1.275 (22a)ₐₙ = 52.500 (22a)

Adjusted infiltration rate (allowing for shelter and wind speed) = (21) x (22a)ₐₙ

(22b)ₐₙ = 0.793 (22b)ₐₙ = 1.312 (22b)ₐₙ = 8.167 (22b)

Calculate effective air change rate for the applicable case:

If mechanical ventilation: air change rate through system

0 (23a)

If exhaust air heat pump using Appendix N, (23b) = (23a) x Fₐₙ, (equation (N4)), otherwise (23b) = (23a)

0 (23b)

If balanced with heat recovery: efficiency in % allowing for in-use factor (from table 4h) = 0 (23c)

192
a) If balanced mechanical ventilation with heat recovery (MVHR) \( (24a)_m = (22b)_m + (23b) \times (1 - (23c) = 100) \) 
\[ (24a), (24a)_1, (24a)_2, (24a)_3, (24a)_4, (24a)_5, (24a)_6, (24a)_7, (24a)_8, (24a)_9, (24a)_{10}, (24a)_{11}, (24a)_{12} \]

b) If balanced mechanical ventilation without heat recovery (MV) 
\[ (24b)_m = (22b)_m + (23b) \] 
\[ (24b), (24b)_1, (24b)_2, (24b)_3, (24b)_4, (24b)_5, (24b)_6, (24b)_7, (24b)_8, (24b)_9, (24b)_{10}, (24b)_{11}, (24b)_{12} \]

c) If whole house extract ventilation or positive input ventilation from outside 
\[ (24c)_m = (22b)_m + (23b) \] 
\[ (24c)_1, (24c)_2, (24c)_3, (24c)_4, (24c)_5, (24c)_6, (24c)_7, (24c)_8, (24c)_9, (24c)_{10}, (24c)_{11}, (24c)_{12} \]

d) If natural ventilation or whole house positive input ventilation from loft 
\[ (24d)_m = (22b)_m + (23b) \] 
\[ (24d)_1, (24d)_2, (24d)_3, (24d)_4, (24d)_5, (24d)_6, (24d)_7, (24d)_8, (24d)_9, (24d)_{10}, (24d)_{11}, (24d)_{12} \]

Effective air change rate - enter (24a) or (24b) or (24c) or (24d) in box (25)

If Appendix Q applies in relation to air change rate, the effective air change rate is calculated via Appendix Q and use the following instead:

\[ (25)_m = \] 

(25)

3. Heat losses and heat loss parameter

Items in the table below are to be expanded as necessary to allow for all different types of element e.g. 4 wall types.

The \( K \)-value is the heat capacity per unit area, see Table 1e

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>Gross area ((\text{m}^2))</th>
<th>Openings ((\text{m}^2))</th>
<th>Net area ((\text{m}^2))</th>
<th>(U)-value ((\text{W}/\text{m}^2\text{K}))</th>
<th>(A \times U) ((\text{W}/\text{K}))</th>
<th>(K)-value ((\text{ki}/\text{m}^2\text{K}))</th>
<th>AxK ((\text{ki}/\text{K}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid door</td>
<td>0</td>
<td>x</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-glazed door</td>
<td>4.0422</td>
<td>x</td>
<td>1.2</td>
<td>4.851</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window *</td>
<td>(U-value = 1.2)</td>
<td>W/m²K</td>
<td>16.559</td>
<td>x</td>
<td>1.145</td>
<td>18.960</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>15.799</td>
<td>1.145</td>
<td>18.090</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof window*</td>
<td>(U-value = 0)</td>
<td>W/m²K</td>
<td>0</td>
<td>x</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Basement floor</td>
<td>0.000</td>
<td>x</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Suspended ground floor</td>
<td>14.255</td>
<td>x</td>
<td>0.981</td>
<td>13.985</td>
<td>23.84</td>
<td>339.8487</td>
<td></td>
</tr>
<tr>
<td>Solid ground floor</td>
<td>26.245</td>
<td>x</td>
<td>0.5716</td>
<td>15.001</td>
<td>110</td>
<td>2886.956</td>
<td></td>
</tr>
<tr>
<td>Basement wall</td>
<td>-</td>
<td>-</td>
<td>=</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>External wall</td>
<td>122.36</td>
<td>-</td>
<td>20.601</td>
<td>101.761</td>
<td>x</td>
<td>2.1</td>
<td>213.699</td>
</tr>
<tr>
<td></td>
<td>122.36</td>
<td>-</td>
<td>19.841</td>
<td>102.521</td>
<td>x</td>
<td>2.1</td>
<td>215.294</td>
</tr>
<tr>
<td>Roof</td>
<td>40.500</td>
<td>-</td>
<td>0</td>
<td>40.500</td>
<td>x</td>
<td>0.14</td>
<td>5.670</td>
</tr>
</tbody>
</table>

Total area of external elements \(\Sigma A\), m²

203.363 \(29a)\)

\| Part wall | 65.461 | x | 0 | 0.000 | 104.05 | 6811.227 |

\| Party wall (party wall \(U\)-value from Table 3.6, \(K\) according to its construction) | 0 | 0 | 0 | 0 |

\| Party ceiling | 0 | 0 | 0 | 0 |

\| Internal wall ** | 106.24 | 104.05 | 11054.02 | 104.05 | 11043.02 |

\| Internal floor | 41.404 | 23.84 | 987.0618 | 23.8 | 985.4057 |

*For windows and roof windows, use effective window \(U\)-value calculated using formula 1/[(1/\(U\)-value) + 0.04] as given in paragraph 3.2

**Include the areas on both sides of internal walls and partitions

Fabric heat loss, W/K = \(\Sigma (AxU)\)

\(26\) \(\ldots (30) + (32) = 272.165 \text{ (33 right)} \)

Heat capacity \(C_m = \Sigma (AxK)\)

\(28\) \(\ldots (30) + (32) + (32a) \ldots (32e) = 4405.04 \text{ (34 right)} \)

Thermal mass parameter \(\text{TMP} = C_m + \text{TA}\) in kJ/m²K

\(34) - (4) = 537.886 \text{ (35 right)} \)

For design assessments where the details of the construction are not known precisely the indicative values of \(\text{TMP}\) in Table If can be used instead of detailed calculation. Also \(\text{TMP}\) calculated seperately can be used in \(\text{(35)}\).

Thermal bridges: \(\Sigma (L \times Y)\) calculated using Appendix K

30.504 \(36)\)

If details of thermal bridging are not known \(36) = 0.15 \times (31)\)

Total fabric heat loss

\(33) \times (30) = 302.670 \text{ (37 right)} \)

\(= 303.395 \text{ (37 left)} \)
Ventilation heat loss calculated monthly

<table>
<thead>
<tr>
<th>(38)ℏm</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>(38)m</td>
<td>58.799</td>
<td>57.917</td>
<td>57.053</td>
<td>52.992</td>
<td>52.232</td>
<td>48.696</td>
<td>48.696</td>
<td>48.041</td>
<td>50.058</td>
<td>52.232</td>
<td>53.769</td>
<td>55.376</td>
</tr>
</tbody>
</table>

Heat transfer coefficient, W/K


Heat loss factor (HLF), W/m²K


Number of days in month

<table>
<thead>
<tr>
<th>(41)m</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>(41)m</td>
<td>31</td>
<td>28</td>
<td>31</td>
<td>30</td>
<td>31</td>
<td>30</td>
<td>31</td>
<td>30</td>
<td>31</td>
<td>30</td>
<td>31</td>
<td>31</td>
</tr>
</tbody>
</table>

4. Water heating energy requirement kWh/year

Assumed occupancy, N

\[ N = 2.498 \] (42)

if TFA > 13.9, \( N = 1 + 1.76 \times \left[ 1 - \exp(-0.000349 \times (\text{TFA}-13.9)) \right] + 0.0013 \times (\text{TFA}-13.9) \)

Annual average hot water usage in litres per day

\[ V_{\text{average}} = (25 \times N) + 36 \] (43)

Reduce the annual hot water usage by 5% if the dwelling is designed to achieve a water use target of not more than 125 litres per person per day (all water use, hot and cold)

<table>
<thead>
<tr>
<th>(44)m</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>(44)m</td>
<td>108.29</td>
<td>104.36</td>
<td>100.42</td>
<td>96.48</td>
<td>92.54</td>
<td>88.60</td>
<td>88.60</td>
<td>92.54</td>
<td>96.48</td>
<td>100.42</td>
<td>104.36</td>
<td>108.29</td>
</tr>
</tbody>
</table>

Energy content of hot water used - calculated monthly = \( 4.18 \times V_{\text{average}} \times n_{\text{c}} \times \Delta T_{\text{m}} / 3600 \text{ kWh/month (see Tables 1b, 1c, 1d) }\)

<table>
<thead>
<tr>
<th>(45)m</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>(45)m</td>
<td>160.6</td>
<td>139.8</td>
<td>149.9</td>
<td>138.5</td>
<td>137.2</td>
<td>127.2</td>
<td>131.4</td>
<td>137.2</td>
<td>138.5</td>
<td>148.9</td>
<td>149.8</td>
<td>160.6</td>
</tr>
</tbody>
</table>

If instantaneous water heating at point of use (no water storage), enter "0" in boxes (46) to (61)

Distribution loss

<table>
<thead>
<tr>
<th>(46)m</th>
<th>0.15 \times (45)m</th>
</tr>
</thead>
</table>

Storage volume (litres) including any solar or WWHRS storage within same vessel

\[ 0 \] (47)

If community heating and no tank in dwelling, enter 110 litres in (47)

Otherwise if no stored hot water (this includes instantaneous combi boilers) enter '0' in (47)

Water storage loss:

a) If manufacturer's declared loss factor is known (kWh/day):

\[ \begin{align*}
\text{Temperature factor from Table 2} & = 0 \quad (48) \\
\text{Energy loss from water storage, kWh/day} & = 0.000 \quad (49)
\end{align*} \]

b) If manufacturer's declared cylinder loss factor is not known:

\[ \begin{align*}
\text{Hot water storage loss factor from Table 2 (kWh/litre/day)} & = 0 \quad (50) \\
\text{If community heating see section 4.3} & = 0 \quad (51) \\
\text{Volume factor from Table 2a} & = 0 \quad (52) \\
\text{Temperature factor from Table 2b} & = 0 \quad (53) \\
\text{Energy lost from water storage, kWh/day} & = 0.000 \quad (54)
\end{align*} \]

Enter (49) or (54) in (55)

Enter (56) in (55)

Water storage loss calculated for each month

\[ \begin{align*}
(56)m & = (55) \times (41), \\
(56) & = 0.000 \quad (56)
\end{align*} \]

If the vessel contains dedicated solar storage or dedicated WWHRS storage,

\[ \begin{align*}
(57)m & = (56)m \times (47) \quad (57) \\
& = 0.000 \quad (58)
\end{align*} \]

Where Vs is Vww from Appendix G3 or (H11) from Appendix H (as applicable)
Primary circuit loss for each month from Table 3
(modified by factor from Table H4 if there is solar water heating and a cylinder thermostat, although not for community DHW systems)

\[
(59)_{\text{m}} = 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad (59)
\]

Combi loss for each month from Table 3a, 3b or 3c (enter "0" if not a combi boiler)

\[
(61)_{\text{h}} = 50.959 \quad 46.027 \quad 50.959 \quad 49.315 \quad 50.959 \quad 49.315 \quad 50.959 \quad 49.315 \quad 50.959 \quad 49.315 \quad 50.959 \quad (61)
\]

Total heat required for water heating calculated for each month

\[
(62)_{\text{h}} = 211.557 \quad 185.809 \quad 199.877 \quad 187.778 \quad 188.197 \quad 187.778 \quad 199.877 \quad 199.081 \quad 211.557 \quad (62)
\]

Solar DHW input calculated using Appendix G or H (negative quantity) (add additional lines if FGRHS and/or WWHRS applies, see appendix G)

\[
(63)_{\text{h}} = 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad (63)
\]

Output from water heater for each month, kWh/month

\[
(64)_{\text{h}} = 211.557 \quad 185.809 \quad 199.877 \quad 187.778 \quad 188.197 \quad 187.778 \quad 199.877 \quad 199.081 \quad 211.557 \quad (64)
\]

Heat gains from water heating, kWh/month

\[
(65)_{\text{h}} = 66.139 \quad 57.984 \quad 62.255 \quad 58.368 \quad 58.372 \quad 58.368 \quad 62.255 \quad 62.126 \quad 66.139 \quad (65)
\]

Internal gains from water heater for each month, kWh/month

\[
(59)_{\text{h}} = 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad 0.000 \quad (59)
\]

Heat losses to air (enter "0" if not a combi boiler, incl. any basement losses)

\[
(66)_{\text{h}} = 124.9 \quad 124.9 \quad 124.9 \quad 124.9 \quad 124.9 \quad 124.9 \quad 124.9 \quad 124.9 \quad 124.9 \quad 124.9 \quad (66)
\]

Lighting gains (calculated in Appendix L, equation L9 or L9a), also see Table 5

\[
(67)_{\text{h}} = 20.032 \quad 17.793 \quad 14.470 \quad 10.955 \quad 8.189 \quad 6.913 \quad 7.470 \quad 9.710 \quad 13.033 \quad 16.548 \quad 19.314 \quad 20.589 \quad (67)
\]

Appliances gains (calculated in Appendix L, equation L13 or L13a), also see Table 5

\[
(68)_{\text{h}} = 223.374 \quad 225.692 \quad 217.881 \quad 207.416 \quad 191.719 \quad 176.966 \quad 167.110 \quad 164.759 \quad 157.031 \quad 148.756 \quad 139.925 \quad 131.572 \quad (68)
\]

Cooking gains (calculated in Appendix L, equation L15 or L15a), also see Table 5

\[
(69)_{\text{h}} = 35.490 \quad 35.490 \quad 35.490 \quad 35.490 \quad 35.490 \quad 35.490 \quad 35.490 \quad 35.490 \quad 35.490 \quad 35.490 \quad 35.490 \quad (69)
\]

Pumps and fans gains (Table 5a)

\[
(70)_{\text{h}} = 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad 3 \quad (70)
\]

Losses e.g. evaporation (negative values) (Table 5)

\[
(71)_{\text{h}} = -100 \quad -100 \quad -100 \quad -100 \quad -100 \quad -100 \quad -100 \quad -100 \quad -100 \quad -100 \quad (71)
\]

Water heating gains (Table 5)

\[
(72)_{\text{h}} = 88.9 \quad 86.3 \quad 81.7 \quad 81.1 \quad 78.5 \quad 75.8 \quad 75.8 \quad 75.8 \quad 81.1 \quad 83.7 \quad 86.3 \quad 88.9 \quad (72)
\]

Total internal gains

\[
(73)_{\text{h}} = 395.8 \quad 393.2 \quad 381.5 \quad 362.9 \quad 341.8 \quad 323.2 \quad 313.9 \quad 316.4 \quad 328.2 \quad 346.8 \quad 367.8 \quad 386.5 \quad (73)
\]

Solar gains calculated using solar flux (Table U3) and associated equations to convert to the applicable orientation.

\[
(74)_{\text{h}} = 53.5^\circ \text{N} \quad 0.9338 \quad \text{Latitude (Table U4)}
\]

Horizontal solar radiation (Table U3), W/m²

\[
(75)_{\text{m}} = 26 \quad 54 \quad 96 \quad 150 \quad 192 \quad 200 \quad 189 \quad 157 \quad 115 \quad 66 \quad 33 \quad 21 \quad (75)
\]

Solar declination, degrees

\[
(76)_{\text{m}} = -0.4 \quad -0.2 \quad 0.0 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.4 \quad 0.2 \quad 0.1 \quad -0.2 \quad -0.3 \quad -0.4 \quad (76)
\]

Tilt of windows θ = horizontal. 90 = vertical

\[
p, \text{deg} = 90.5
\]
Calculation constants for each month for one angle of window. More angles require another table.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60.0</td>
<td>0.255</td>
<td>-0.329</td>
</tr>
<tr>
<td>2</td>
<td>150.0</td>
<td>1.415</td>
<td>-3.240</td>
</tr>
<tr>
<td>3</td>
<td>240.0</td>
<td>0.848</td>
<td>-1.993</td>
</tr>
<tr>
<td>4</td>
<td>330.0</td>
<td>0.398</td>
<td>-0.397</td>
</tr>
</tbody>
</table>

Solar flux

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14699</td>
<td>28.118</td>
<td>46.677</td>
<td>76.064</td>
<td>98.595</td>
<td>103.51</td>
<td>97.474</td>
<td>79.977</td>
<td>58.144</td>
<td>33.908</td>
<td>17.628</td>
<td>11.527</td>
</tr>
<tr>
<td>2</td>
<td>40.113</td>
<td>67.305</td>
<td>89.68</td>
<td>107.58</td>
<td>117.63</td>
<td>115.62</td>
<td>111.94</td>
<td>104.56</td>
<td>95.863</td>
<td>73.707</td>
<td>47.853</td>
<td>34.458</td>
</tr>
<tr>
<td>3</td>
<td>31.076</td>
<td>54.890</td>
<td>76.259</td>
<td>101.59</td>
<td>117.63</td>
<td>117.63</td>
<td>112.68</td>
<td>101.15</td>
<td>86.431</td>
<td>61.375</td>
<td>37.543</td>
<td>26.376</td>
</tr>
</tbody>
</table>

Access factor

<table>
<thead>
<tr>
<th>Table 6d</th>
<th>Area (m²)</th>
<th>Table 6b</th>
<th>Table 6c</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60.0</td>
<td>0.77 x 4.03 x 0.9</td>
<td>0.63 x 0.7</td>
</tr>
<tr>
<td>2</td>
<td>150.0</td>
<td>0.77 x 6.4606 x 0.9</td>
<td>0.63 x 0.7</td>
</tr>
<tr>
<td>3</td>
<td>240.0</td>
<td>0.77 x 1.4315 x 0.9</td>
<td>0.63 x 0.7</td>
</tr>
<tr>
<td>4</td>
<td>330.0</td>
<td>0.77 x 4.8192 x 0.9</td>
<td>0.63 x 0.7</td>
</tr>
</tbody>
</table>

Solar gains in watts, calculated for each month

| (83)u = | 126.423 | 223.929 | 328.837 | 444.490 | 531.259 | 541.994 | 516.482 | 449.594 | 368.508 | 253.576 | 152.997 | 107.170 |
| (83)u = | 522.19 | 617.17 | 710.30 | 807.40 | 893.09 | 986.59 | 893.38 | 766.02 | 696.79 | 600.34 | 493.64 | 375.34 |
| (84)u = | 522.19 | 572.45 | 644.87 | 719.17 | 767.70 | 757.66 | 727.92 | 676.82 | 623.54 | 549.77 | 490.24 | 472.20 |

7. Mean internal temperature

Temperature during heating periods in the living area from Table 9, T3, (°C)

Utilisation factor for gains for living area, ηu, (see Table 9a)

| (86)u = | 1.000 | 0.999 | 0.999 | 0.997 | 0.991 | 0.974 | 0.925 | 0.954 | 0.989 | 0.998 | 0.999 | 1.000 |
|         | 0.999 | 0.999 | 0.999 | 0.999 | 0.997 | 0.991 | 0.974 | 0.925 | 0.954 | 0.989 | 0.998 | 0.999 |

Responsiveness of main heating system (see Table 4a or 4d)

Mean internal temperature in living area T3, (follow steps 3 to 7 in Table 9c)


Heating control (Table 4e)

2
Temperature during heating periods in rest of dwelling from Table 9, T1,°C

<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
</table>

8. Space heating requirement

Set T1 to the mean internal temperature obtained at step 11 of Table 9b, so that T1,m = (93)m and recalculate the utility factor for gains using Table 9a

<table>
<thead>
<tr>
<th>Utility factors for gains, ( n_{\text{g},n} ) : (see separate worksheet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0.99917 )</td>
</tr>
</tbody>
</table>

8f. Space heating - removed, unused

9a. Energy requirements - Individual heating systems, including micro-CHP

For any space heating, space cooling or water heating provided by community heating, use the alternative SAP worksheet 9b.

Space heating:

- Fraction of space heat from secondary/ supplementary system (Table 11) \( 0^* \) if none
- Fraction of heating from main system(s) \( 0^* \) if none
- Fraction of heating from main system 2 \( 0^* \) if no second main system enter "0*"
- Fraction of total space heat from main system \( 0^* \) if none

Space cooling:

- Fraction of space heat from secondary/ supplementary system (Table 11) \( 0^* \) if none
- Fraction of heating from main system(s) \( 0^* \) if none
- Fraction of heating from main system 2 \( 0^* \) if no second main system enter "0*"
- Fraction of total space heat from main system \( 0^* \) if none
Efficiency of main heating system 1 (in %)
(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c; for gas and oil boilers see 9.2.1)
If there is a second main system complete (207)
Efficiency of main space heating system 2 (in %)
(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c; for gas and oil boilers see 9.2.1)
Efficiency of secondary-supplementary heating system, % (from Table 4a or Appendix E)

Cooling System Energy ratio (see table 10c)

<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kwh/year</td>
</tr>
</tbody>
</table>

Space heating requirement (calculated above)


Space heating fuel (main system 1), kwh/month


Space heating fuel (main system 2), kwh/month


Space heating fuel (secondary), kwh/month


Water heating:

Outlet from water heater (calculated above)


Efficiency of water heater, %
(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the ‘DHW efficiency adjustment’ column of Table 4c, for gas and oil boilers use the summer efficiency, see 9.2.1)
If water heating by hot-water-only boiler, (217)w = value from database record for boiler or Table 4a otherwise if gas/oil boiler main system used for water heating, (217)w = value calculated each month using equation (8) in section 9.2.1 otherwise if separate hot water only heater (including immersion) (217)w = applicable value from Table 4a otherwise (other main system 1 or 2 used for water heating) (217)w = (216)

Fuel for water heating, kwh/month


Total = Σ(219)1…12 = 2609.32 (219)w

(219)w = (64)w x (204) x 100 + (207)

Fuel for water heating, kwh/month


(219)w = (64)w x (204) x 100 + (207)

Water heating:

Outlet from water heater (calculated above)


Efficiency of water heater, %
(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the ‘DHW efficiency adjustment’ column of Table 4c, for gas and oil boilers use the summer efficiency, see 9.2.1)
If water heating by hot-water-only boiler, (217)w = value from database record for boiler or Table 4a otherwise if gas/oil boiler main system used for water heating, (217)w = value calculated each month using equation (8) in section 9.2.1 otherwise if separate hot water only heater (including immersion) (217)w = applicable value from Table 4a otherwise (other main system 1 or 2 used for water heating) (217)w = (216)

Total = Σ(219)1…12 = 2609.32 (219)w

(219)w = (64)w x (204) x 100 + (207)

Space cooling:

Space cooling fuel, kwh/month


Total = Σ(221)1…8 = 0.00 (221)

Annual totals

<table>
<thead>
<tr>
<th>kWh/year</th>
<th>kWh/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space heating fuel used, main system 1</td>
<td>18794.15 (211 right) 19087.32 (211 left)</td>
</tr>
<tr>
<td>Space heating fuel used, main system 2</td>
<td>0.00 (213)</td>
</tr>
<tr>
<td>Space heating fuel used, secondary</td>
<td>0.00 (215)</td>
</tr>
<tr>
<td>Water heating fuel used</td>
<td>2609.32 (219 right) 2608.45 (219 left)</td>
</tr>
<tr>
<td>Space cooling fuel used (if there is a fixed cooling system, if not enter 0)</td>
<td>0.00 (221)</td>
</tr>
</tbody>
</table>
### Appendix

#### Water

Appendix generated electricity used/net electricity heating secondary (215) 0.00 x 216
Space cooling (221) 0.00 x 217
Boiler flue fan 45 (230e)
Maintaining electric keep-hot facility for gas combi-boiler (230f) 0 x
Pump for solar water heating (231) 0 x 232
Pump for storage WWRHS (see section G.3.3) (230g) 0 x

Total electricity for the above, kWh/year $\Sigma(230a) \ldots (230h) = 75$ (231)

#### Electricity for lighting (calculated in Appendix L)

<table>
<thead>
<tr>
<th>Fuel kWh/year</th>
<th>Fuel price (Table 12) £/p</th>
<th>Fuel cost £/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>353.78</td>
<td>355.65</td>
<td>355.65 (232 right)</td>
</tr>
<tr>
<td>232 (232 left)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Energy saving/generation technologies (Appendices M, N and Q)

Electricity generated by PVs (Appendix M) (negative quantity) 0.00 (233)
Electricity generated by wind turbine (Appendix M) (negative quantity) 0.00 (234)
Electricity used or net electricity generated by micro-ChP (Appendix N) (negative if net generation) 0.00 (235)
Electricity generated by hydro-electric generator (Appendix M) (negative quantity) 0.00 (235a)

#### Appendix Q Items: annual energy (Items not already included on a monthly basis)

<table>
<thead>
<tr>
<th>Fuel kWh/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>353.78</td>
</tr>
<tr>
<td>355.65</td>
</tr>
</tbody>
</table>

Total energy delivered for all uses (211) \ldots (214) = 43883.67 (238 right) 22126.42 (238 left)

#### 10a. Fuel costs - individual heating systems including micro-ChP

<table>
<thead>
<tr>
<th>Fuel kWh/year</th>
<th>Fuel price (Table 12) £/p</th>
<th>Fuel cost £/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space heating - main system 1 (211)</td>
<td>0.00</td>
<td>654.04 (240 right)</td>
</tr>
<tr>
<td>Space heating - main system 2 (211)</td>
<td>0.00</td>
<td>664.24 (240 left)</td>
</tr>
<tr>
<td>Space heating - secondary (215)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Water heating (electric off-peak tariff)

| High rate fraction (Table 13, or Appendix F for electric CPSUs) | 0 |
| Low rate fraction 1.0 - (243) | 4 |
| High rate cost (219) \times (243) | 0 \times 0 \times 0.01 = 0.00 |
| Low rate cost (219) \times (244) | 2609.32 \times 0 \times 0.01 = 0.00 |

Water heating cost (other fuel) (219) | 2609.32 \times 3.48 \times 0.01 = 90.80 (247 right) |

Energy for lighting (212) | 353.78 \times 13.19 \times 0.01 = 46.91 (250 right) |

Additional standing charges (Table 12) 174 (251)

#### Energy saving/generation technologies

Energy generated by PVs (233) | 0.00 x 0 x 0.01 = 0.00 (252a) |
Energy generated by wind turbine (234) | 0.00 x 0 x 0.01 = 0.00 (252b) |
Electricity used/net generated by micro-ChP (235) | 0.00 x 0 x 0.01 = 0.00 (252c) |
Electricity generated by hydro-electric generator (235a) | 0.00 x 0 x 0.01 = 0.00 (252c) |

Appendix Q items: repeat lines (253) and (254) as needed

| <item description>, energy saved (236a) | 0.00 x 0 x 0.01 = 0.00 |
| <item description>, energy used (237a) | 0.00 x 0 x 0.01 = 0.00 |

---

199
| **Total energy cost** | 
|----------------------|----------|
| (240) . . . (242) + (245) . . . (254) = | 975.40 |
| | 985.81 |

11a. **SAP rating - individual heating systems including micro-CHP**

**Energy cost deflator (Table 12):**

\[
\text{Energy cost factor (ECF)} = \frac{(255) \times (256)}{(4) + 45.0} = 3.228 \quad (257 \text{ right})
\]

\[
\text{Energy cost factor (ECF)} = \frac{(255) \times (256)}{(4) + 45.0} = 3.263 \quad (257 \text{ left})
\]

**SAP rating (section 13)**

| 55 | 54 |

**SAP Band (table 14)**

| D |

12a. **CO2 emissions - individual heating systems including micro-CHP**

<table>
<thead>
<tr>
<th>Energy kWh/year</th>
<th>Emission factor kg CO2/kWh</th>
<th>Emissions kg CO2/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space heating - main system 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(211)</td>
<td>x</td>
<td>0.216</td>
</tr>
<tr>
<td></td>
<td>(211)</td>
<td>x</td>
</tr>
<tr>
<td>Space heating - main system 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(213)</td>
<td>0.00</td>
<td>x</td>
</tr>
<tr>
<td>Space heating - secondary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(215)</td>
<td>0.00</td>
<td>x</td>
</tr>
<tr>
<td>Energy for water heating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(218)</td>
<td>2609.32</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>2608.45</td>
<td>x</td>
</tr>
<tr>
<td>(for a DHW-only community scheme use (361) to (373) instead of (264))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space and water heating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(261) + (262) + (263) + (264) =</td>
<td>4623.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(265 right)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(265 left)</td>
<td></td>
</tr>
<tr>
<td>Space cooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(221)</td>
<td>0.00</td>
<td>x</td>
</tr>
<tr>
<td>Electricity for pumps, fans and electric keep hot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(231)</td>
<td>75.00</td>
<td>x</td>
</tr>
<tr>
<td>Electricity for lighting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(232)</td>
<td>353.78</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>355.65</td>
<td>x</td>
</tr>
<tr>
<td>Energy saving/generation technologies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity generated by PVs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(233)</td>
<td>0.00</td>
<td>x</td>
</tr>
<tr>
<td>Electricity generated by wind turbine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(234)</td>
<td>0.00</td>
<td>x</td>
</tr>
<tr>
<td>Electricity used or net electricity generated by micro-CHP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(235)</td>
<td>0.00</td>
<td>x</td>
</tr>
<tr>
<td>Electricity generated by hydro-electric generator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(235a)</td>
<td>0.00</td>
<td>x</td>
</tr>
<tr>
<td>Appendix Q items: repeat lines (270) and (271) as needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;item 1 description&gt;, energy saved</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(236a)</td>
<td>0.00</td>
<td>x</td>
</tr>
<tr>
<td>&lt;item 1 description&gt;, energy used</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(237a)</td>
<td>0.00</td>
<td>x</td>
</tr>
<tr>
<td>Total CO2, kg/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Sigma(265) . . . (271) = 4845.69)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(272 right)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(272 left)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dwelling CO2 Emission Rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\frac{(272) - (4)}{(272) + (4) + 45} = 59.16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(273 right)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(273 left)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\frac{(272) - (4)}{(272) + (4) + 45} = 38.18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(274 right)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(274 left)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EI rating (section 14)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(274 right)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(274 left)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EI BAND (Table 14)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 13a. Primary energy - individual heating systems including micro-CHP

Same as 12a using primary energy factor instead of CO₂ emission factor to give primary energy in kWh/year

<table>
<thead>
<tr>
<th>Energy kWh/year</th>
<th>P.e. factor kWh/kWh</th>
<th>Primary energy kWh/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space heating - main system 1</td>
<td>40000 x 1.22</td>
<td>23313.08</td>
</tr>
<tr>
<td>Space heating - main system 2</td>
<td>1000 x 1.22</td>
<td>1220.00</td>
</tr>
<tr>
<td>Space heating - secondary</td>
<td>1000 x 1.22</td>
<td>1220.00</td>
</tr>
<tr>
<td>Energy for water heating</td>
<td>8100 x 1.22</td>
<td>9840.00</td>
</tr>
</tbody>
</table>

(for a DHW-only community scheme use (361) to (373) instead of (264))

<table>
<thead>
<tr>
<th>Space and water heating</th>
<th>26112.24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space cooling</td>
<td>0.00 x 0 = 0.00</td>
</tr>
<tr>
<td>Electricity for pumps, fans and electric keep hot</td>
<td>75 x 3.07 = 230.25</td>
</tr>
<tr>
<td>Electricity for lighting</td>
<td>353.78 x 3.07 = 1086.10</td>
</tr>
<tr>
<td>Electricity for lighting</td>
<td>355.65 x 3.07 = 1091.83</td>
</tr>
</tbody>
</table>

Energy saving/generation technologies

- Electricity generated by PVs | 0.00 x 0 = 0.00 |
- Electricity generated by wind turbine | 0.00 x 0 = 0.00 |
- Electricity used or net electricity generated by micro-CHP | 0.00 x 0 = 0.00 |
- Electricity generated by hydro-electric generator | 0.00 x 0 = 0.00 |

Appendix Q items: repeat lines (270) and (271) as needed

- <item 1 description>, energy saved | 0.00 x 0 = 0.00 |
- <item 1 description>, energy used | 0.00 x 0 = 0.00 |

Total Primary energy kWh/year

- Sum = 27428.59

Dwelling Primary energy rate kWh/m²/year

- sum ÷ (4) = 334.89

- 339.31