Thin Internal Wall Insulation (TIWI)

Measuring Energy Performance Improvements in Dwellings Using Thin Internal Wall Insulation

Summary Report

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LEEDS SUSTAINABILITY INSTITUTE

LEEDS BECKETT UNIVERSITY

Department for Business, Energy & Industrial Strategy

Contents

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Executive Summary

The Leeds Sustainability Institute at Leeds Beckett University were contracted by BEIS to quantify the benefits and risks associated with installing internal wall insulation (IWI) and thin internal wall insulation (TIWI) retrofits into solid wall homes.

In order to deliver this, a holistic approach was adopted and the project was split into four main sections, each of which has an accompanying Annex to this summary report:

> Annex A: Review of existing literature as well as primary investigations using house surveys, householder questionnaires and installer focus groups into the sociotechnical barriers to IWI and TIWI.
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> Annex B: Technical evaluation of the performance of IWI and six novel TIWI retrofits installed in field trial solid wall Test Houses using before and after building performance evaluations.
>
> Annex C: Modelling of the impact on annual energy consumption, EPC rating, overheating risk, condensation risk and moisture accumulation made by IWI and TIWI retrofits in a range of UK house archetypes.
>
> Annex D: Laboratory testing of test walls using hygrothermal chambers to quantify the change in moisture and thermal performance of solid brick walls when they are insulated with IWI and TIWI to determine how weathering affects heat flux, surface and interstitial condensation risk and moisture accumulation.

Annex A describes the findings from surveys undertaken in 100 solid wall homes, which indicated that almost all homes will require remedial works or items to be relocated prior to IWI and TIWI retrofits indicating that cost of these may be more than is currently assumed. A survey of 180 individuals was also undertaken which identified the most important motivators for having retrofits were to reduce energy bills, that it was good value for money and would make homes warmer. The most important factor was the cost of installation, while improvements to house prices and appearance were not considered important. Further barriers were identified in four different focus groups with installers, specifically that they didn't enjoy undertaking IWI retrofits, and they thought administrative burdens were too high to take on ECO retrofits. Finally, it was observed that installers believed that manufactures' specifications were made to be deliberately unachievable so that any possible underperformance or unintended consequence can be blamed on the installers not the product.

Table 0-1 summarises the results of the tests undertaken in Annex B. As can be seen both TIWI and IWI can reduce the whole house heat loss measured via the heat transfer coefficient (HTC) by similar amounts. The law of diminishing returns means that doubling insulation thickness only results in an additional 3% saving in HTC between IWI and TIWI 1. All the savings are attributed to the improvements in fabric performance since airtightness tests that were undertaken before and after each retrofit showed that none of the retrofits made homes more airtight.

Table 0-1 Measured impact on thermal performance resulting from TIWI retrofit

		Material	Thickness (mm)	Heat loss area that was insulated	Cost per m²	Measured U-value of baseline wall (W/m²K)	Measured U-value of insulated wall (W/m²K)	U-value reduction	HTC before retrofit (W/K)	HTC after retrofit (W/K)	HTC reduction
Test House A	IWI	Phenolic board	70	23%	£157	2.11	0.30	86%	205	168	18%
	TIWI 1	PIR	27	23%	£102	2.11	0.78	63%	205	175	15%
	TIWI 2	Aerogel	14	23%	£150	2.11	0.76	64%	205	178	13%
Test House B	TIWI 3	EPS	22	19%	£113	2.01	0.98	49%	236	201	15%
	TIWI 4	Cork render	20*	19%	£107	2.01	1.36	32%	236	196	17%
Test House C	TIWI 5	Latex rolls	10	32%	£96	2.10	1.30	38%	177	160	10%
	TIWI 6	Thermo-paint	1*	38%	£30	1.30	1.25	4%	160	149	7%†

Other findings from the Building Performance Evaluation investigations in the test houses suggest that some uninsulated solid walled homes may not achieve their setpoint temperatures during colder periods and that even installing IWI or TIWI may not noticeably improve thermal comfort. Furthermore, the investigations identified that the rooms in roofs in solid wall homes may not be well insulated and can have high levels of infiltration. A follow up study was therefore undertaken to investigate the impact of installing IWI and TIWI into existing rooms in roofs. It found that these retrofits could reduce whole house heat loss by around 20%, which is more than was achieved by the IWI product when installed on walls. Moreover, it was observed that TIWI was cheaper and quicker to retrofit into rooms in roofs as it could overboard the existing walls and ceilings and also resulted in less thermal bridging.

Annex C described investigations using dynamic simulation models to evaluate the impact of IWI and TIWI on annual fuel bills, energy and carbon emissions. Thermal models were used to describe thermal bridging risks that may be introduced by IWI and TIWI retrofits and hygrothermal simulations were used to predict how water may accumulate in solid walls following wall retrofits.

Table 0-2 highlights the main findings from these modelling exercises. As can be seen in the table adding TIWI to solid walls may result in lower annual fuel bills for householders in the region of £50 to £90, whereas IWI may achieve savings in the region of £130. However, the amount of glazing (wall area available to insulate), the infiltration rates (air exchanges that can bypass the insulation) and the length of time a home is heated for (heating hours) substantially affect the potential savings that may be achieved. Thus, IWI and TIWI retrofits may only save some households 3% off their space heating bills if they have little external wall area and high infiltration rates, whereas households with large areas of external wall and low levels of infiltration may reduce their fuel bills by up to 59%.

* Due to application method, exact thickness is uncertain

† This saving is within the 10% error for the test and statistical analysis and disaggregation of HTC gives low confidence in measured result, partly due to warm external conditions during testing

Table 0-2 Modelled impact on thermal performance resulting from TIWI retrofit

Insulation	Modelled annual fuel bill savings‡	Modelled annual GHG reduction	Simulated reduction in wall water content (kg/m²)	Simulated reduction in inner leaf water content (kg/m²)	Simulated % time at risk of mould and rot	Breathable open vapour product
Base case	-	-	45%	59%	0.2%	No
IWI	£128	4.6%	4%	-6%	11.3%	No
TIWI 1	£89	3.2%	17%	17%	5.3%	No
TIWI 2	£89	3.3%	31%	41%	2.8%	Yes
TIWI 3	£70	2.5%	24%	29%	4.3%	No
TIWI 4	£46	1.7%	39%	52%	0.7%	Yes
TIWI 5	£49	1.4%	40%	53%	0.6%	No
TIWI 6	£10	0.4%	44%	58%	0.2%	Yes

Thermal modelling also investigated the effect of an *enhanced* retrofit (following PAS 2030 guidance) and a *reduced* retrofit, where reveals around fenestrations, returns on party and partition walls, and the intermediate floor void were left uninsulated. In the uninsulated state, these locations were already predicted to be condensation risks in homes, but that these risks could be eliminated when *enhanced* IWI and TIWI retrofits were undertaken. However, if *reduced* retrofits were installed, thermal bridging would become even more extreme at these junctions. Furthermore, there would be a substantial risk of surface condensation when IWI was installed, and a somewhat increased risk when TIWI was installed.

Conversely, when considering the party wall junction, the opposite was the case: in an *advanced* IWI and TIWI retrofit the party wall return was insulated and this substantially increased the risk of surface condensation in the adjoining property. A *reduced* retrofit at the party wall (i.e. no insulation on the party wall reveal) increased the existing risk to a lesser extent.

Hygrothermal simulations predict that IWI and TIWI increases the risk of timber rot to timber joists in the inner brick leaf; conventional IWI could increase risk by around 11%, though TIWI may increase risk by less than half this amount, and breathable systems further lower risk. Additionally, after a three-year simulated test, conventional IWI retrofits were predicted to increase moisture content in the walls, unlike TIWI where no year-on-year increases were predicted to occur.

Condensation risk and moisture accumulation risks associated with IWI and TIWI retrofits were also evaluated via laboratory investigations described in Annex D. Solid brick test walls were exposed to accelerated weathering cycles in hygrothermal chambers to measure changes to moisture movement in the brick and temperature profiles with and without IWI and TIWI installed. The results showed a greater amount of water accumulation in the inner leaf of the wall with IWI compared to the walls with TIWI installed.

The laboratory investigations also found that IWI substantially introduced risks of interstitial condensation behind the insulation boards and TIWI somewhat increased the risk. However, both IWI and TIWI were observed to reduce the risk of surface condensation in homes.

‡ Assuming identical wall areas insulated

The following summary points describe the main findings from the investigations into TIWI and IWI retrofits:

- TIWI installed on walls can reduce whole house heat loss in solid wall homes by 10% to 17%.
- IWI reduces whole house heat loss by only 3% more than equivalent TIWI.
- Installing IWI or TIWI in rooms in the roofs of homes can reduce whole house heat loss by 20%.
- Savings are affected by the amount of wall area insulated, infiltration rates, heating hours and thermal resistance of the product, resulting in possible domestic fuel bill savings of 3% to 59%.
- Infiltration rates were not affected by the IWI or TIWI wall retrofits.
- Neither uninsulated nor insulated solid wall homes tested achieved thermal comfort.
- Stated costs of IWI and TIWI may be underestimates as 90% of homes require remedial work.
- Installers are reluctant to install IWI and do not feel supported to do so.
- Uninsulated solid wall homes are predicted to be at risk of surface condensation.
- IWI and TIWI *enhanced* retrofits are predicted to eliminate surface condensation risks.
- IWI and TIWI *reduced* retrofits are predicted to increase surface condensation risks.
- Insulating party wall returns increases surface condensation risks for neighbours.
- IWI introduces substantial interstitial condensation risks.
- TIWI introduces some interstitial condensation risks.
- IWI substantially increases water accumulation and risk of rot in timber joists in walls.
- TIWI does not substantially increase water accumulation and risk of rot in timber joists in walls.
- Breathable systems have lower moisture accumulation risks than non-breathable alternatives.

1 Summary Report Introduction

1.1 Research Project Overview

Thin internal wall insulation (TIWI) could play a role in UK energy policy, though the extent to which it can contribute to emissions targets, increase retrofit rates of solid wall homes, reduce fuel poverty, improve thermal comfort and mitigate unintended consequences is not fully understood.

On behalf of the Department for Business, Energy and Industrial Strategy (BEIS), Leeds Beckett University have investigated the potential of TIWI to achieve warmer homes and lower fuel bills with fewer unintended consequences than conventional internal wall insulation (IWI).

Five output reports describe the research and results from this project, these are:

1. Summary Report
2. Annex A, Introduction to TIWI: Literature, Household & Industry Reviews
3. Annex B, TIWI Field Trials: Building Performance Evaluation
4. Annex C, Predicting TIWI Impact: Energy & Hygrothermal Simulations
5. Annex D, Moisture Risks of TIWI: Laboratory Investigations

1.2 TIWI Summary Report Overview

This report presents an overview of the TIWI research project, highlighting the key findings from each of the research activities undertaken, and discusses what implications these findings have for TIWI in the context of the UK's domestic energy efficiency policy.

This report is structured as follows:

- Section 2, Research Design
- Section 3, Literature, Household, Building and Installer Surveys
- Section 4, IWI & TIWI Field Tests
- Section 5, Building Performance Evaluation Tests
- Section 6, Energy and Hygrothermal Simulation
- Section 7, Laboratory Investigations into IWI and TIWI Moisture Risks
- Section 8, Policy Implications

2 Research Design

In this interdisciplinary research project, six different complementary research phases were combined, as summarised in Figure 2-1.

Figure 2-1 Overview of TIWI project research design

Three Test Houses were secured and used to provide baseline cases against which the products could be applied and building performance evaluation (BPE) activities conducted as part of the field tests phase. The modelling phase and laboratory tests phase also used these case studies as their reference points.

Research phases 1 to 5 took place between 2017 and 2019 by researchers at Leeds Beckett University (LBU), while phase 6 was completed during the same period by Lucideon Ltd and LBU. Each phase had a specific role in contributing to the overall aims of this research project.

Each of the research phases are described in detail in the Annexes, while this summary report brings together all the findings from each of the research activities to provide an overview and discuss what the implications of TIWI may be for future policy decisions.

3 Literature, Household, Building and Installer Surveys

This section presents the research undertaken to identify the existing knowledge of, and barriers to, IWI retrofits in the UK. It summarises the current literature then presents findings from 180 questionnaires, specifically comparing how householders value cost, the hassle factor and energy savings associated with retrofits. Results from site visits that had been undertaken to identify if unintended consequences had manifested in five historical retrofits are then presented. Further, the results from surveys of 100 solid wall dwellings are described and the practical barriers to IWI retrofits that often escalate costs are listed. Finally, results from four focus groups each with five IWI installers are described, focussing on how communication can be improved to raise standards in the industry.

3.1 IWI Thermal Performance, Moisture and Fire Risk

A review of the existing literature on IWI is presented in Annex A to this report, the majority of which concerns the potential to introduce moisture issues into homes due to imperfect installations causing additional thermal bridging.

Although little has been published on flammability of IWI retrofits in homes, IWI products are not currently considered to present a significant increase in the risk of fire. However, additional fire testing of all products installed as a system is recommended, since information pertains only to the products in isolation and the increased fuel load of combustible IWI presents some fire risk.

A range of thermal performance improvements resulting from IWI retrofits is reported in the literature reflecting the diversity of materials and specifications that are available. The literature suggests IWI appears to reduce household greenhouse gas emissions (GHG) in the region of 5% to 10%.

3.2 Investigating Householder Acceptance of TIWI; Questionnaires

A questionnaire was developed to investigate householder motivations and barriers of IWI retrofits. 143 responses were collected from Leeds City Council and Leeds Beckett University staff as well as 37 householders in Yorkshire. The questionnaire investigated general perceptions around IWI retrofits and used conjoint analysis to quantify specifically the relative importance of cost, energy saving potential and hassle factor. Discussions on the representativeness of these findings for the wider population and the methodology used for the conjoint analysis on the data obtained from the survey are presented in Annex A and summarised here.

In general, the respondents were more favourable about products and technologies that they had an awareness of, indicating the need to promote retrofits generally to increase their uptake. Important motivators for having retrofits were to reduce energy bills, to have a warmer home and to provide good value for money. Conversely, the least important motivator was that it may improve the value or appearance of homes. Two to three days was the period of time most commonly expected for the duration of a retrofit. The most popular retrofits were solar panels (26%), new windows (20%) and a new boiler (20%); only 3% preferred IWI. The conjoint analysis specifically identified that the most important factor driving respondents' preferences for IWI was the cost of installation, followed by the perceived energy savings and finally the hassle factor. This may be useful in identifying price points for insulation products according to how much energy they save in homes. A more diverse sample would be required to investigate if this finding was representative for the UK.

3.3 Identifying Barriers to IWI and the Hassle Factor: Building Surveys

The cost of installing IWI appears to be a major barrier for increasing retrofit rates. However, the initial quoted cost of the product and installation itself is only one aspect of this; dealing with specific issues on site can add substantial additional cost. In this research 100 homes were surveyed to measure and count the frequency of obstructions and features which may be contributing to additional costs for IWI retrofits. This could have the potential to identify if there are any beneficial characteristics that novel IWI products may have, specifically, if TIWI retrofits may avoid any of the barriers that increase the cost of IWI retrofits. The full results of the findings from the 100 solid wall homes that were surveyed can be found in Annex A and are summarised here.

In 95% of cases at least one wall mounted obstruction would require removal. More concerning, however, was that radiators, bathroom furniture, boilers, telephone sockets and utility meters were observed to be obstructions in many cases and so require third parties to become involved in the retrofits, dramatically increasing costs as shown in Figure 3-1.

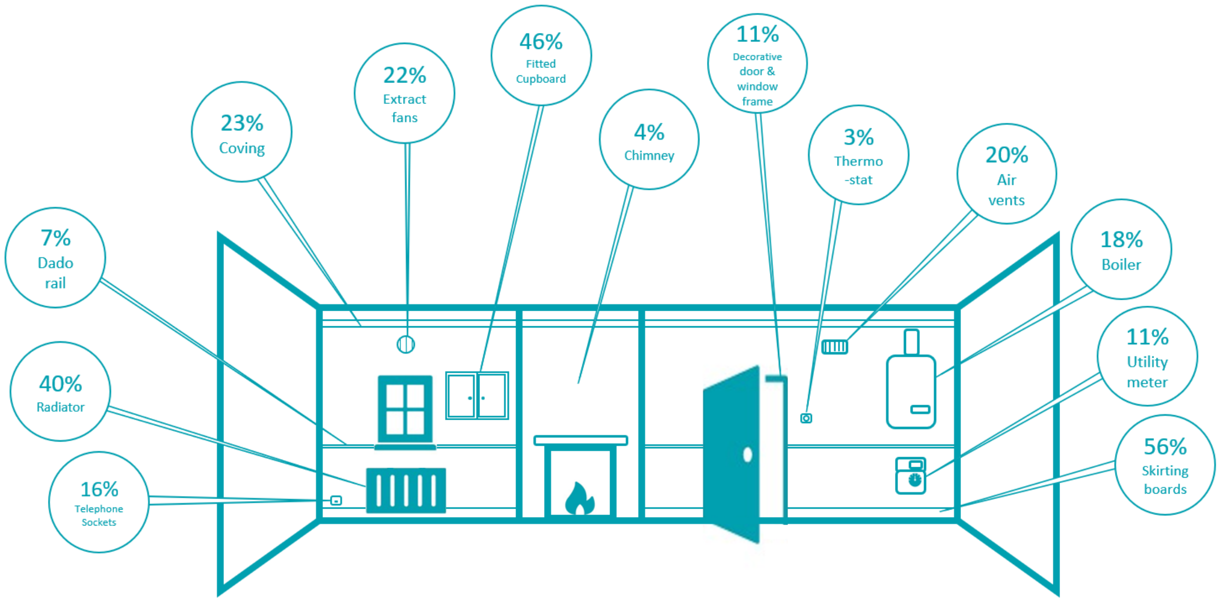

Figure 3-1 Proportion of walls surveyed that had obstacles to IWI retrofits

The surveys also identified that in almost all cases remedial works will be needed prior to any wall insulation being installed. For example, damp was observed in 9 out of 10 homes; a quarter of walls were already damaged; one in 10 homes had no ventilation; and 13% of walls were not flat (posing issues for rigid board solutions). Additionally, half of all walls already had plasterboard installed which would need to be removed before any retrofit could take place.

Skirting boards and coving were regularly less than 30mm deep, thus only the thinnest TIWI (<10mm) could be installed with existing wall joinery in place. Finally, window and door details posed several problems; around one third had insufficient space for reveal boards and 31% of doors and 11% of windows were installed in line with internal surfaces meaning they may need to be moved prior to IWI being fitted. All these issues will have cost implications for IWI and TIWI retrofits.

These surveys have confirmed that the building characteristics and features themselves may be limiting the opportunity for IWI and in many cases can increase the cost of the installation. The work has also been useful in identifying that many barriers will affect all IWI and TIWI retrofits, however, there may be some features of a TIWI that may make it more successful in overcoming some of these barriers. Specifically, TIWI that is less than 10mm, not based on rigid boards and which can reuse existing fittings for wall mounted objects may have more potential to disrupt the existing markets. These surveys reflect only the features observed in 100 solid wall homes so cannot be extrapolated to be nationally representative figures, though no other large-scale survey of this kind has been undertaken.

3.4 Historical Surveys of IWI

As noted in the literature, moisture risks may be introduced into homes following IWI retrofits, though may not manifest until several years after the installation. Therefore, surveys were undertaken of five dwellings that had undergone IWI retrofits between 6 to 18 years previously. The methodology and results for these are presented in full in Annex A and are summarised here. During the surveys, a blower door test was undertaken in accordance with ATTMA standards (ATTMA, 2010) to measure the airtightness of the dwellings. In addition, an induced pressure of ±50 Pa was used in the homes when conducting leakage detection using handheld smoke puffers and thermography where possible. This was not possible in all dwellings due to concerns around the effect on vulnerable householders.

The characteristics of the five dwellings and summary results are described in Table 3-1. Overall, surface condensation risk was not commonly present, though some air movement behind IWI was observed. At complicated details (for example, gas meters, fenestrations, corners) and when subsequent changes to the wall were made (wall penetrations and openings that had been covered or bricked up), additional thermal bridges, air movement and discontinuities (missing insulation or poorly fitted insulation) were observed. Excessive infiltration rates were found in the dwellings (generally around ground floors and doors), indicating IWI retrofits did not have a whole house approach. Bridging was a common problem at stone door thresholds and junctions between walls and ground floors.

Table 3-1 Surveyed Dwellings with Historic IWI Retrofits

No.	Dwelling type	Wall type	Age of dwelling	Airtightness (m^3/ (h.m^2) @ 50Pa)	Δ T during thermographic survey (K)	Insulation	Target wall U-value (Wm^2/K)§	Date of retrofit	Condensation risk observed (fRsi < 0.75)	Notes
1	Mid Terrace	9-inch Solid brick	1900s	4.85	6.8	IWI 90mm Gyproc (front) IWI 100mm	0.3	2012	No	Single whole house retrofit
2	End Terrace	9-inch Solid brick	1918	11.15	10.3	Unknown IWI	n/a	2000	No	Multiple retrofits over time
3	Ground floor flat	Cavity brick	1976	n/a	7.8	Unknown CWI and IWI	n/a	2005	No	Multiple retrofits over time
4	Mid Terrace	Concrete System	1965	n/a	8.4	EWI 60mm (front)	n/a	2001	Yes	Multiple retrofits over time
5	Ground floor flat	Cavity brick	1976	n/a	6.1	Unknown CWI and IWI	n/a	2005	Yes	Multiple retrofits over time

§ It was common for landlords to have no record of the type of IWI installed, thus no target U-value could be calculated.

Although the surveys were not able to inspect interstitial condensation risk, the findings from these five case studies indicate that IWI does not necessarily lead to elevated surface condensation risk in homes. To understand the risk on a national scale, more homes of different ages and construction types need to be surveyed and interstitial condensation assessments made.

3.5 Understanding Installer Perceptions around TIWI: Interviews and Focus Groups

Interviews with the contractors involved in this project led to the development of topic guides for four focus groups with 20 current IWI installers. The methodology and results of these are presented in Annex A, and the three major themes that emerged that have relevance for policy makers and standards agencies are described here.

First, IWI is viewed as impractical in situations other than new builds, extensions and conversions. It is too time consuming and therefore expensive to remove pipes, skirting boards, and to replace window ledges etc. It’s not a job that people enjoy, given it can be awkward to use and the product itself can be itchy and dusty. Installers wanted a product that is simple to install and repair and often favoured rigid boards since they were more familiar with these.

The second barrier is that participants did not view installing IWI as a particularly skilled job and so did not see the point of training. PAS 2030 standards are not well known, and the bureaucracy associated with ECO-funded projects deters small businesses from pursuing these projects. The standards themselves and the people who inspect sites are not always seen as credible, therefore PAS 2030 standards are perceived as irrelevant.

The final barrier is that even when builders are following a well-designed specification, they encounter situations on site that mean they need to deviate from the specification. Sometimes they can be aware of how such deviations reduce the effectiveness of insulation but there is nothing they can do. Sometimes they are unaware of the consequences of the adaptations they make, and sometimes they have heard of potential problems but are sceptical of them.

There was very little interest in training for installing IWI as it is not seen as a technically challenging task. Learning usually takes place on site from more experienced colleagues. There would need to be some benefit to people if they are to attend external training, for example a certificate or accreditation that could provide a competitive advantage, or that the training enables people to install the insulation more effectively, faster or cheaper. Apps were not viewed as an ideal source of information, as smartphone use is discouraged on site. Information sheets inside products are unlikely to be read, although printing a few key points on the products themselves may be effective.

4 IWI & TIWI Field Tests

This section presents the justification for the selection of the TIWI and IWI that were tested in this project, as well as the approach to the field tests that were undertaken to collect BPE data. Following this is a description of the Test Houses and the retrofits that took place.

4.1 TIWI and IWI products

A review of the different IWI products on the market or near market is summarised in Table 4-1. While not a definitive list, it serves to highlight the range of products available. There are too many specific brands and variations of TIWI and IWI to usefully reproduce here and this review cannot account for new products that emerge or indeed older products that no longer trade. The ability of a TIWI to improve the U-value of solid brick walls is determined by the products' thickness and conductivity. It is also noteworthy that there is a substantial variation in the cost of the different products, though this is only the cost of the product itself, not the cost of the product fully installed. Some IWI may take longer to install than others and some may require decoration or more materials to be installed in addition to the product than others. Thus, the prices shown here may not reflect the actual relative cost effectiveness of each product. This will be investigated further in Section 4.4.

Table 4-1 Summary of available TIWI and IWI

Product type	Potentially Breathable	Thickness (mm)	λ value (W/mK)	Approximate U-value applied to solid brick wall of 2.09 W/ m^2K**	Product cost per m^2 (£ ex VAT)	Application
Phenolic, PUR, PIR, EPS etc. foam	No	12.5 - 100	0.018 - 0.040	0.19 - 1.04	£1.5 - £76	Plasterboard laminate or between batons
Aerogel blankets	Yes	10 - 60	0.014	0.21 - 0.72	£59 - £252	Magnesium board laminates or between batons
Cork Insulating render	Yes	10 - 75	0.037 - 0.058	0.40 - 1.79	£8 - £28	Direct
Latex foam rolls	No	10 - 20	0.019	0.66 - 1.01	£24 - £45	Direct
Mineral wool blankets or slabs	Yes	25 - 100	0.035 - 0.038	0.3 - 0.87	£1.40 - £10	Between batons
Vacuum Insulated Panels (VIPs)	No	20 - 40	0.0036 - 0.008	0.20 - 0.36	£78 - £111	Between batons
Wood fibre board (inc. cement)	Yes	20 - 100	0.037 - 0.048	0.36 - 0.92	£7 - £55	Between batons or directly applied
Calcium silicate board	Yes	30 - 50	0.059	0.8 - 1.06	£49	Direct
Thermo-reflective aerogel paint	Yes	1	0.014	2.02	£22	Direct

Six TIWI were taken forward to be tested in this project, and for comparison, one conventional IWI commonly used in policy funded retrofits that strive to achieve 0.3 W/m^2K U-value. Mineral wool blankets, VIP, Wood fibre and Calcium silicate boards were too thick to be considered TIWI (i.e. >25mm). Table 4-2 identifies the products that were selected.

** Average U-value measured for test houses in this study

Ideally, to increase the ability to compare the results each TIWI would have been tested in the same Test House. However, given that the experiment would only run for one winter it was necessary to use three separate Test Houses so that two TIWI interventions could be tested in each. Comparing the products used in each house against each other may be possible since the only variable should be the insulation. Comparing the TIWI between houses is less straight forward. As much as possible the TIWI installed in each Test House had similar performance (R-value), so that comparisons would be useful.

Table 4-2 TIWI and IWI selected for testing

TIWI	Product type	Potentially Breathable	Insulation Thickness (mm)	Thickness[††] including 5mm air gap, board & 3mm plaster skim (mm)	Combined R value (m^2K/W)	Justification	Test House
IWI	Phenolic foam plasterboard laminate	No	60	77	2.71	• Standard IWI solution for funded retrofits (Building Regulations compliance) • Reference as a "conventional IWI"	A
1	PIR plasterboard laminate	No	15	35	0.85	• Common non-funded retrofit • Industry up selling as enhanced dry lining	A
2	Aerogel blankets	Yes	10	21	0.82	• Novel material • Thinnest laminate board available • Similar install method and performance to PIR • Only breathable board available	A
3	EPS plasterboard laminate	No	13	30	0.50	• Cheapest alternative to dry lining • Possible DIY product	B
4	Cork Insulating render	Yes	18	21	0.35	• Novel product and installation • Potential alternative to plaster skim • Similar performance at this thickness to EPS boards • Breathable	B
5	Latex foam rolls	No	10	10	0.19	• Novel product and installation • Similar to decorator's industry skill set • Possible alternative to wallpapering	C
6	Thermo-reflective aerogel paint	Yes		0.014	0.01	• Novel product • Thinnest product available • DIY application • Lowest cost option	C

†† Assumed air gap behind the laminate boards and solid wall and the plaster skim thickness and the board thickness varies by product

4.2 Field test design

As described, six TIWI and one conventional IWI were tested in Test Houses A, B and C. The field trials were undertaken over the winter of 2017/18 (November to April). As an additional research activity, a further Test House was sought in winter of 2018/19 to investigate the effect of TIWI installed in a room in roof retrofit and is discussed at the end of Annex B.

As shown in Figure 4-1, there were two main test phases for each product: 1) coheating where quasi *steady state* conditions could be maintained to identify the heat transfer coefficient which was used to evaluate the performance of the insulation and to calibrate the dynamic simulation models (DSM); and 2) monitoring of the internal conditions during normal heating patterns, or a so called *dynamic state* which was used to evaluate benefits to thermal comfort and heat up and cool down times. Each of these needed to be tested before and after the insulation. Test House A had a North facing wall which allowed for more detailed surface temperature measurements to be taken. This made it possible to compare the thermal bridging in retrofits with uninsulated vs insulated reveals and returns in this home. The field-testing regime was as follows:

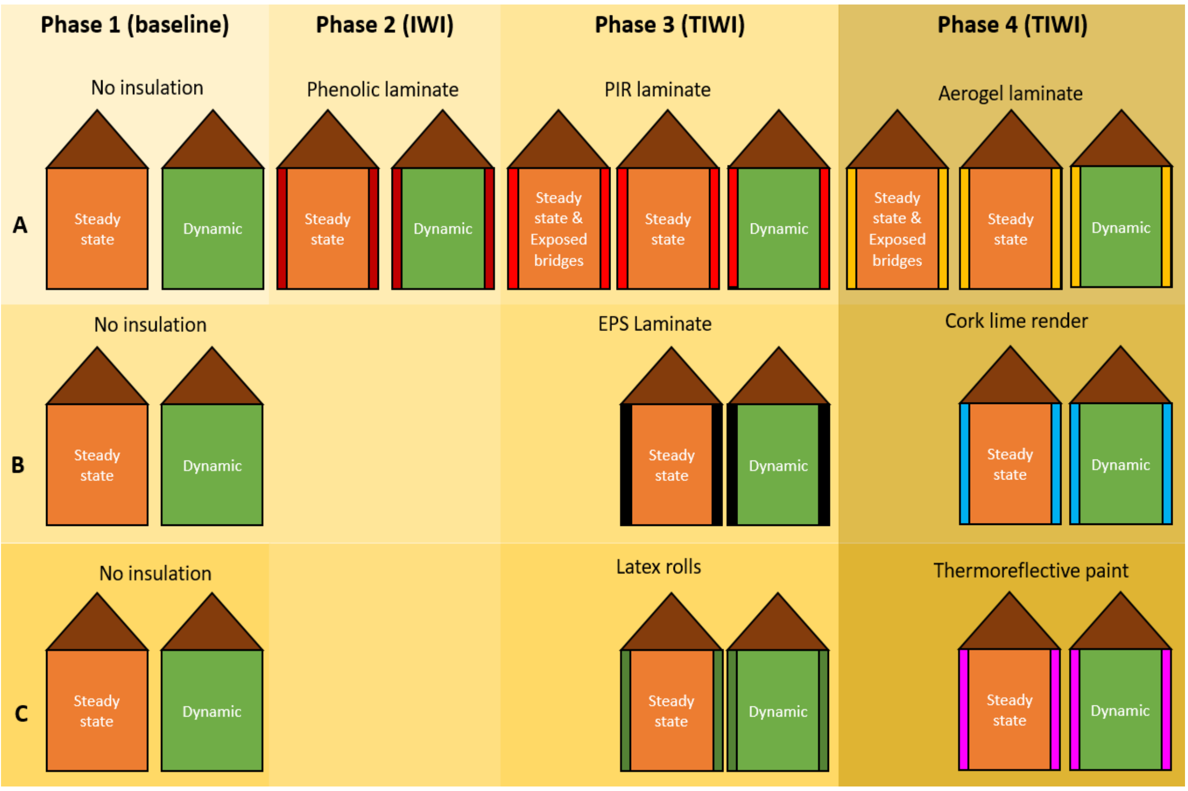

Figure 4-1 Schematic of field trial phases in Test House A, B and C

The total period that properties were available for testing the products limited the duration of each phase and meant that the conventional IWI and the investigation into the effects of exposed bridges could only be undertaken in Test House A. Test House A was secured at the beginning of the test program, while Test House B and C followed later. Before each phase began, the insulation installed in the previous phases needed to be removed and so delays around removing and installing the different insulation further limited the time available to test and monitor performance. The next section describes how the Test Houses were identified and following this, a description is presented of the phases that occurred in each house as well as the limitations that were faced.

4.3 Sampling

As with most BPE field trials, purposeful, non-probability sampling was used to select the Test Houses, i.e. the houses selected had to have certain characteristics to be considered for inclusion in the trial. A range of different social landlords form West Yorkshire was contacted to find houses for testing. A minimum of 2 external solid walls in each dwelling was required to ensure marginal improvements made by novel IWI products could be measured. In addition, the properties had to be reasonably representative of a building type that is common in the UK and could account for a large proportion of the housing stock. This led us to the following archetype hierarchy:

- 9-inch solid brick detached or semi-detached, or end, or mid through terraces
- 9-inch solid brick back-to-back end terraces
- Non-traditional (concrete) solid wall detached or semi-detached or through terraces

Furthermore, an additional sub criterion was applied that the properties had a sufficiently large area of North facing wall, or should not have predominantly south facing walls, so that robust U-value measurements could be reliably obtained.

Finally, to ensure that conditions could be fully controlled and monitored and since the proposed tests are intrusive and protracted, the properties had to be uninhabited for the duration of the 6-month testing period. These restrictions necessarily limited the availability of Test Houses and required a detailed knowledge of the sample prior to selecting the homes. Therefore, convenience sampling was undertaken drawing on existing networks of 3 local authorities and 10 registered social landlords and housing charities around Yorkshire. Enquiries were made between July and November 2017 and resulted in the properties being identified in **Error! Not a valid bookmark self-reference.**.

Table 4-3 Sample properties

House Code	House Archetype	Suitability	North Wall	Decision to use
A	9-inch brick, mid through terrace	No major concerns, 2 neighbours	Yes	Yes
B	9-inch brick, mid through terrace	New kitchen and bathroom	No	Yes
C	9-inch brick, back to back, end terrace	Third floor has external wall	Yes	Yes
D	9-inch brick, mid through terrace	Fibre board already installed	No	No
E	No fines end terrace	Expanded polystyrene already installed	Yes	No
F	No fines mid terrace	Insufficient external wall	No	No
G	No fines mid terrace	Still tenanted	No	No
H	No fines mid terrace	Withdrawn by council	No	No
I	No fines mid terrace	Withdrawn by council	No	No
J	No fines mid terrace	Insufficient external wall	No	No
K	9-inch brick, back-to-back end terrace	Difficult to test	No	No
L	9-inch brick, back-to-back mid terrace	Withdrawn by council for EWI scheme	No	No
M	2 semi-detached 1930 cottage flats,	Cavity wall on inspection	Yes	No
N	Adapted pre 1900 semi-detached	Brick, stone and block with IWI and plasterboard	Yes	No
O	9-inch brick detached gate house	Listed, ownership change; sold by council	Yes	No
P	9-inch brick end terrace back to back	South-facing gable, insufficient external wall	No	No

From these, houses A, B and C were determined to be the most appropriate, satisfying more of the requirements than other homes and so they were taken forward as Test Houses and they are described in detail in the following sections. These are referred to as Test House A, B and C respectively.

4.4 Retrofit costs

This section provides an overview of the costs associated with the different TIWI retrofits described in the previous sections. The costs presented here are based on the actual costs to undertake the installation of the specific TIWI and the installers that were used for these retrofits. It is worth stating that if other product manufacturers and installers were used with different organisational structures, economies of scale, overheads or levels of competence and quality, the costs may have been different.

Figure 4-2 **Error! Reference source not found.**shows a summary of the costs according to their major spend category assuming all the retrofits were installed on the same house (same surface area) to simplify the comparisons. When considered as an average across all TIWI types the decoration, fixings, product and installer costs are roughly 14%, 7%, 38% and 41% respectively. However, the ratios for individual TIWI vary substantially.

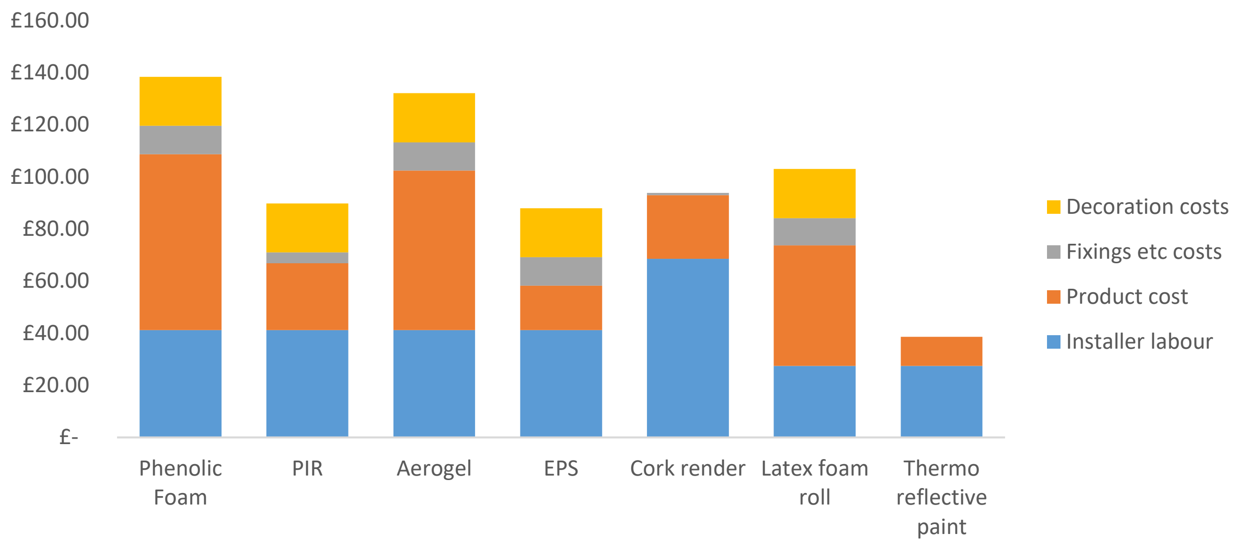

Figure 4-2 TIWI installation costs per m^2 assuming identical retrofits

Error! Reference source not found. Important issues to note are listed here:

- TIWI was on average 30% cheaper than conventional IWI

Rigid laminate boards are as expensive to install as conventional IWI, while render is more expensive since multiple visits were needed. Only latex roll which was applied in a similar way to wallpapering and thermo-reflective paint made savings in installation costs. TIWI therefore made cost savings if the products were cheaper, required fewer revisits or avoided decoration.

- Installer costs were based on number of person days not size (m^2) of retrofit

Regardless of whether a wall was 30m^2 or 40m^2, it had the same "cost" to install since installers would work a shorter or longer day accordingly though still price the work by the day. Therefore, extrapolations of cost per m^2 may be misleading. However, the areas insulated in the three Test Houses are relatively similar and any effect is minor.

- Insulating render added an additional installation stage, increasing duration and cost

The finishing coat to the insulated render could only be installed after the base insulation render had dried. Thus, this doubled the duration of the installation (hassle factor) as well as the installer costs compared to the others, which could be installed and finished in one go.

- Decoration was required in all retrofits, except render and paint

Needing additional decoration added an extra day of labour and material costs as well as extending the duration of the installation. In the case of insulated render and thermo-reflective paint, it may be that additional decoration could be deemed necessary in order to be in keeping with existing decoration in the house. However, the finish could be considered acceptably smooth and clean following the retrofit, meaning additional decoration costs may or may not be needed. On average however, decoration represented only £20 per m² or 10-20% of the costs.

- Shapes of rooms can considerably increase wastage and cost

The wall areas in Test House A and B were relatively similar (approximately 30m²), however, in Test House B, 34 laminate boards were needed compared to 21 in Test House A. This was due to peculiar room geometry and fenestrations (e.g. a bay window in Test House B, which had more corners, etc.), thus direct comparisons against surface area treated may be subject to large ranges according to the simplicity or complexity of the wall being treated.

- Novel fixing systems are more expensive

Although the EPS laminates were cheaper per board than the PIR laminates, they were provided with a novel, more expensive fixing system compared to conventional dot and dab. This increased their installation costs making them less competitive than they may otherwise have appeared. It is not clear what additional benefits this fixing method achieved.

Although there are several limitations with the representativeness of the data, the comparisons can be useful in describing the general costs associated with different TIWI and IWI. Labour costs are a significant contribution of the installation costs. Similar product types have similar installation costs, regardless of their fixing systems or materials. The cork render required two visits unlike the other TIWI: 1) to install the base coat render, then 2) to install the finish layer plaster once dried. This extra visit adds additional cost. Product costs themselves vary considerably; the overall cost of laminate boards is not proportional to their thermal performance. These data are interesting and informative and explain some of the complexities around applying simple cost ranges to TIWI. The full breakdown of costs for this project are presented in Table 4-4**Error! Reference source not found.**.

The values provided here reflect the costs that were incurred in these specific retrofits for the purposes of comparison. The range of IWI and TIWI costs from £30 to £149 per m² are lower than that found by the Retrofit for the Future: analysis of cost data report £123 to £368 per m² (SWEET, 2014) and more in line with the more recent BEIS investigation into retrofit costs of £55 to £140 per m² (Palmer et al., 2017). This suggests the cost of retrofits may have fallen in recent years, although it is not known if the same methodology was used for each study. In addition, there were hidden costs of the retrofit; for example, in Test House B the gable windows had been replaced with UPVC double glazing, however the original window installers had previously failed to make good the edging plaster and brick work, instead covering the omissions with large PVC panelling. The IWI installers therefore had to commit additional labour to correct this prior to the retrofit commencing. These costs were not included in the comparisons since these costs could have been incurred to any of the Test Houses, however, they ran to several hundreds of pounds. The cost of unknown remedial work is often excluded from retrofit cost assessments despite being an essential part of retrofit.

More research to understand costs associated with preparing for retrofit is needed to inform national policy since current government cost estimates for retrofits do not include these (Palmer et al., 2017) and this research has found they will be substantial, and can more than outweigh the savings to fuel bills.

Table 4-4 Retrofit Installation cost breakdown

	Product	Unit cost	No.	Total cost (Including VAT)	Product cost per m²
IWI	Laminate boards	£112.56	21	£2363.76	£76.67
	Plaster skim	£10.00	6	£61.66	£2.00
Phenolic Foam laminate	Fixing nails	£30.00	1	£30.00	£0.97
	Adhesive	£8.00	36	£288.00	£9.34
	Person days	£240.00	6	£1440.00	£46.71
	Decorative finish	£660.00	1	£660.00	£21.41
	Total			**£4,843.42**	**£157.10**
	Laminate boards	£42.85	21	£899.89	£29.19
	Plaster skim	£10.00	6	£61.66	£2.00
TIWI 1	Fixings	£30.00	1	£30.00	£0.97
	Dot and Dab	£10.00	5	£52.50	£1.70
PIR laminate	Person days	£240.00	6	£1440.00	£46.71
	Decorative finish	£660.00	1	£660.00	£21.41
	Total			**£3,144.05**	**£101.98**
TIWI 2	Laminate boards	£43.80	49	£2146.20	£69.61
	Primer	£67.00	1	£67.00	£2.17
Aerogel laminate	Breathable plaster	£25.00	6	£154.15	£5.00
	Adhesive	£9.70	16	£155.20	£5.03
	Person days	£240.00	6	£1440.00	£46.71
	Decorative finish	£660.00	1	£660.00	£21.41
	Total			**£4,622.55**	**£149.94**
	Laminate boards	£28.56	35	£999.60	£32.55
TIWI 3	Plaster skim	£10.00	6	£61.42	£2.00
	Fixing nails	£30.00	1	£30.00	£0.98
EPS laminate	Adhesive	£8.00	36	£288.00	£9.38
	Person days	£240.00	6	£1440.00	£46.89
	Decorative finish	£660.00	1	£660.00	£21.49
	Total			**£3,479.02**	**£113.29**
TIWI 4	Insulation render	£55.20	12	£662.40	£21.57
	Insulating plaster	£24.00	8	£192.00	£6.25
Cork render	PVA	£31.08	1	£31.08	£1.01
	Person days	£240.00	10	£2400.00	£78.15
	Decorative finish	£660.00	0	£0.00	£0.00
	Total			**£3285.48**	**£106.98**
	Foam rolls	£270.00	6	£1620.00	£42.95
TIWI 5	Adhesive	£44.82	6	£268.92	£7.13
	Edging tape	£29.76	1	£29.76	£0.79
Latex foam roll	Sealant	£5.94	6	£35.64	£0.94
	Primer	£31.08	1	£31.08	£0.82
	Person days	£240.00	4	£960.00	£25.45
	Decorative finish	£660.00	1	£660.00	£17.50
	Total			**£3,605.40**	**£95.58**
	Tubs of paint	£65.00	6	£390.00	£8.74
TIWI 6	Person days	£240.00	4	£960.00	£21.52
	Decorative finish	£660.00	0	£0.00	£0.00

Thermo-reflective paint	Total			£1,350.00	£30.27

4.5 Test Houses

As mentioned, the dwellings were solid wall terraced homes with 2 external walls which, according to the English Housing Survey, represents the most common form of solid wall dwellings with approximately 2.1 million being found in England. It is worth pointing out that with only 2 external walls, when the external doors and windows are taken into consideration, the available area for insulation as a proportion of the entire thermal envelope of the dwelling can be relatively small. As the English Housing Survey states that over 50% of homes are either mid terraces or flats, this may be important when considering the national impact of IWI and TIWI (DCLG, 2016). This also suggests that homes with larger wall areas may achieve higher savings than those measured in this project. In all Test Houses, however, enough external wall area was deemed available to gain reliable *in situ* heat flux measurements. The extent of the retrofits undertaken, including information on the wall surface areas that were insulated, is presented in Table 4-5.

Table 4-5 Summary of Test House retrofits

Test Dwelling	TIWI Retrofit	Total heat loss envelope (m²)	Area of external wall (m²) excluding fenestrations	Area of external wall retrofitted (m²)	Proportion of external wall retrofitted	Proportion of heat loss envelope retrofitted
A	Phenolic laminate (IWI)	132.63	65.82	30.38	46%	23%
	PIR laminate	132.63	65.82	30.38	46%	23%
	Aerogel laminate	132.63	65.82	30.38	46%	23%
B	EPS laminate	164.43	75.04	30.71	41%	19%
	Insulated render	164.43	75.04	30.71	41%	19%
C	Latex rolls	116.58	80.70	37.72	47%	32%
	Thermo reflective paint	116.58	80.70	44.60	55%	38%

Field trials necessarily mean that not all the parameters of the experiment can be controlled exactly so it is necessary to understand the limitations experienced. The following section describes the features of the dwellings, the retrofit and the testing protocols undertaken for each house.

4.5.1 Test House A

Test House A, shown in Figure 4-3, was a 9-inch solid brick through terrace orientated North-South. It had a half-plan, mid-height basement and a room in roof, neither of which were altered during the test. Plans are provided in Figure 4-4. There were several features of note in Test House A; no carpets were fitted, which may have reduced the airtightness of the dwelling, and although functional double-glazing PVC units were fitted in each room, it had relatively non-airtight wooden front and rear external doors. In addition, the cellar door was a simple internal wooden door and the cellar itself had an exposed South wall since the terrace was built on a slope. Also, the ceiling to the ground floor was already insulated. There was no over shading on the dwelling and the open fireplaces had been boarded up, though ventilation to the chimney was provided via air vents.

There were no other air vents or trickle vents, except for an extractor fan in the bathroom. The room in the roof had been insulated in the rafters and insulation was observed in the knee walls and boxed in ceiling to the bedrooms below. The tests in Test House A were carried out as shown in Figure 4-1, with each installation of insulation being removed in advance of the next test phase commencing. Test House A was orientated North-South, which afforded the opportunity to undertake detailed surface temperature measurements and investigate the effects of having exposed thermal bridges, thus, this additional test sub phase was adopted here that did not occur in the other Test Houses. In addition to the tests taking place in Test House A, the internal temperature of the neighbouring dwelling on the East side was measured throughout the experiment duration. It was not possible to gain access to the neighbours on the West side.

Insulation was applied to identical wall areas in each test phase in Test House A to ensure the results were comparable. The total wall area covered was 30.83m^2 of which 6.18 m^2 were returns to the party wall. Insulation was applied to both ground floor external walls as well as both first-floor bedroom walls. The first-floor bathroom was not insulated since the landlord did not wish to change their bathroom suite; this provided the opportunity to investigate if leaving rooms uninsulated has any unintended consequences. The kitchen wall units were removed (as it was due for replacement by the landlord) and so this allowed the entire wall to be insulated. Landlords of the three Test Houses described often only insulating external kitchen and bathroom walls that are accessible, leaving areas behind built-in cupboards and the bathroom suite uninsulated, until they are due to be replaced.

Figure 4-3 North Façade of Test House A

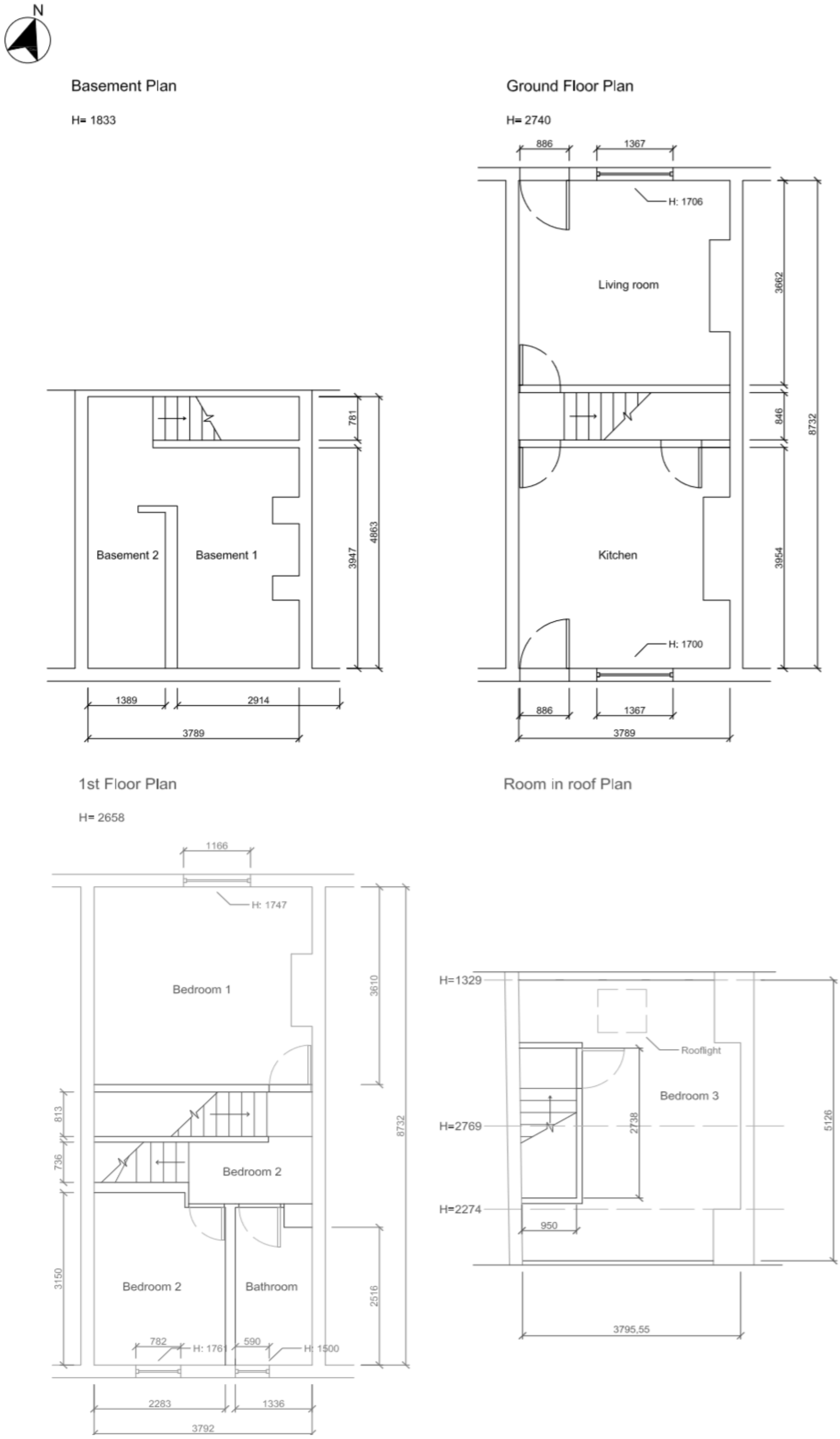

Figure 4-4 Plan of Test House A

4.5.2 Test House B

Test House B, shown in Figure 4-5, is also a 9-inch solid brick through terrace, though this time it is orientated East-West; the plans can be seen in Figure 4-6. The house had a full height basement the entire width of the house, and a room in roof, though again, neither of these were altered during the test. No carpets were fitted in the first and second floors or the circulation spaces, which may have affected the infiltration rates, though there was a laminate floor to the entire ground floor. Other things to note are that although the cellar door was merely an internal wooden door there were functional PVC double glazed windows with trickle vents and external doors throughout. The fireplaces had been boarded over and replaced with air vents, and the only other air vents were mechanical extracts in the kitchen and bathroom. Similarly, to House A, there was no notable shading onto the property and the cellar had one exposed external wall to the East, since the dwelling was again built on a slope.

In Test House B the experiment ran as per Figure 4-1 and again identical wall areas were treated to ensure comparability between the two TIWI installed. Only the living room and both first floor bedrooms were installed with IWI. This is because the dwelling had a new kitchen and bathroom and so the landlord would not usually install IWI here until they were being replaced, thus, these were not insulated in this test. Since the walls were orientated East-West it was not possible to take precise measurements of surface temperatures to explore these discontinuities since solar gains caused by sunlight warming the house from the outside skew U-value measurements. Shielding was therefore erected to cover the area where heat flux was being measured so that the U-value measurements were not affected by solar gains. It was not possible to gain access to measure temperatures in the neighbouring dwellings which limited the information known about the party wall heat loss, although, as in all the Test Houses heat flux measurements through all elements including the party walls were taken to inform this. In total, 30.71m^2 of wall was installed with insulation, of which 6.79 m^2 were returns to the party wall.

Figure 4-5 East Façade of Test House B

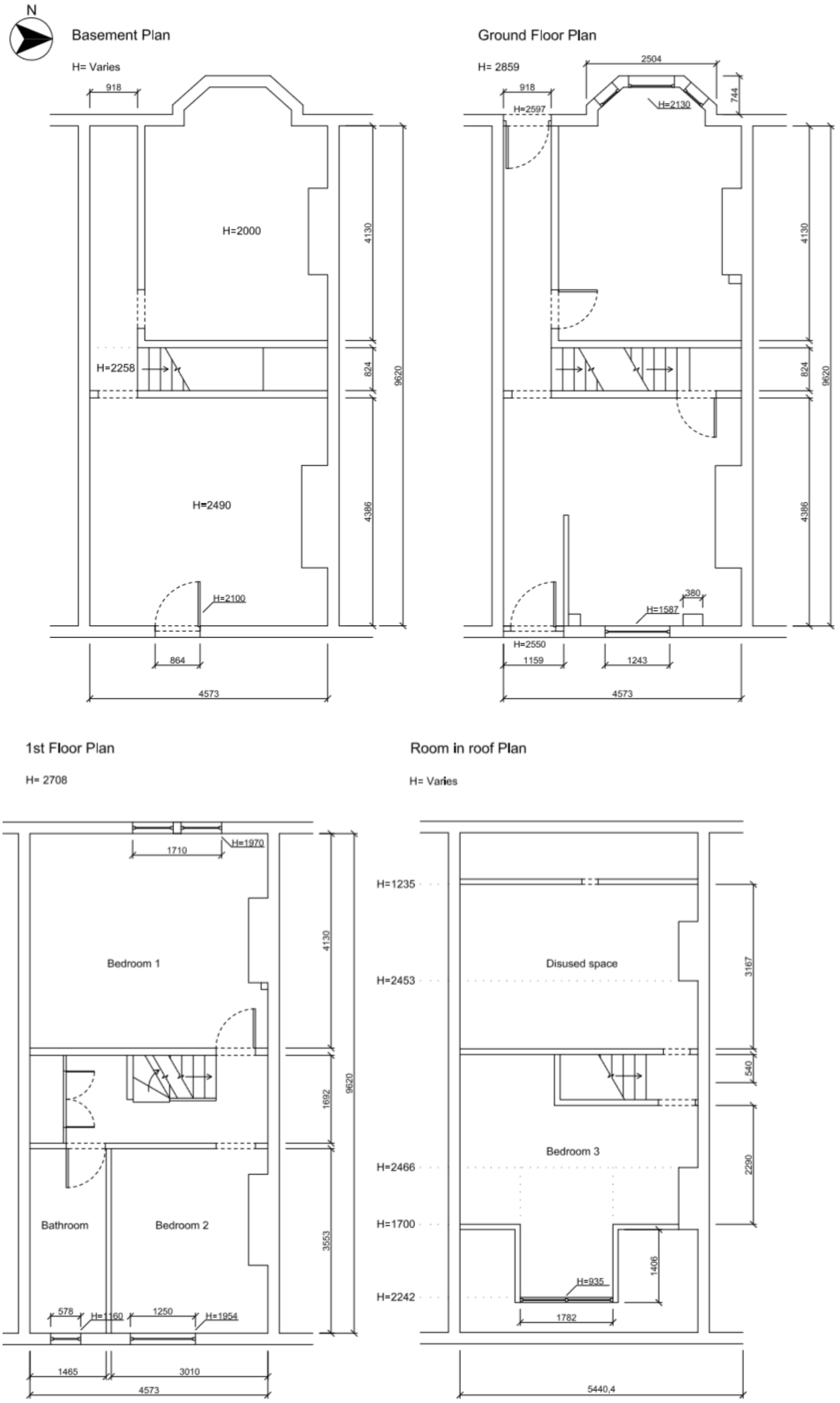

Figure 4-6 Plan of Test House B

4.5.3 Test House C

Test House C, shown in Figure 4-7, was again a 9-inch solid brick property and was also a Back to Back, meaning it had neighbours to the rear and side rather than just the sides. Since House C was an end of terrace, it had a gable wall and therefore still had two external walls, as shown in Figure 4-8 and had more external wall area than Houses A or B.

Things to note in this property are again that there were no carpets in the house, however, there was a wooden floor in the living room which would provide some additional airtightness benefit. The cellar door was particularly draughty, although the front door and all the windows were functional double-glazed PVC including trickle vents. Also, the chimney stack represented a relatively large proportion of the gable wall, essentially acting as a buffer or bypass space to the outside that homes without chimneys do not have. The open fires had been boarded up as in Test House A and B, with air vents installed in their place. The only other air vent was in the bathroom. Again, there was a full height cellar though this time it was completely underground since the street here was not built on a slope. In the room in roof, the knee walls and the sloping roof appeared to be insulated.

The tests ran as per Figure 4-1, though with a slight change. The first TIWI (Latex Rolls) was installed on the Ground and First floors, as per the retrofits in Test House A and B. Both walls to the ground floor living room were insulated as well as the small area of wall in the kitchen. On the first floor, again, both walls in the main bedroom were insulated as was all the accessible wall in the bathroom above the tiling around the bath and toilet. Again, the room in roof and cellar were not changed during this test. It was not possible to access the neighbouring dwellings to record internal air temperatures. In total, 37.72m^2 of external wall area was retrofitted though no returns were installed in this dwelling.

For the final TIWI, thermo-reflective paint, a slight adaptation was made due to an unforeseen complication. It became apparent that the removal of the latex rolls could damage the walls and thus compromise the tests as well as result in possible delays and extra costs. However, since Test House C has exposed external walls in the room in roof (unlike Test House A and B) there was the opportunity to install the thermo-reflective paint here, and still be able to collect enough data to compare performance with the baseline bare brick regarding U-value measurements and changing surface temperatures, comfort levels and heat up and cool down behaviour. To ensure sufficient product was installed to generate a measurable change in the whole house heat loss, thermo-reflective paint was also installed directly on top of the latex rolls. This meant that the baseline value for the reduction in heat transfer coefficient would be the post latex roll retrofit scenario. This also provided the additional benefit of being able to investigate the effect of installing two TIWI in a staged retrofit. Direct cross comparisons between all TIWI would still be possible via the modelling exercises. The total wall area where thermo-reflective paint was applied, was therefore greater at 44.60m^2.

Figure 4-7 North Facing Gable Wall of Test House C

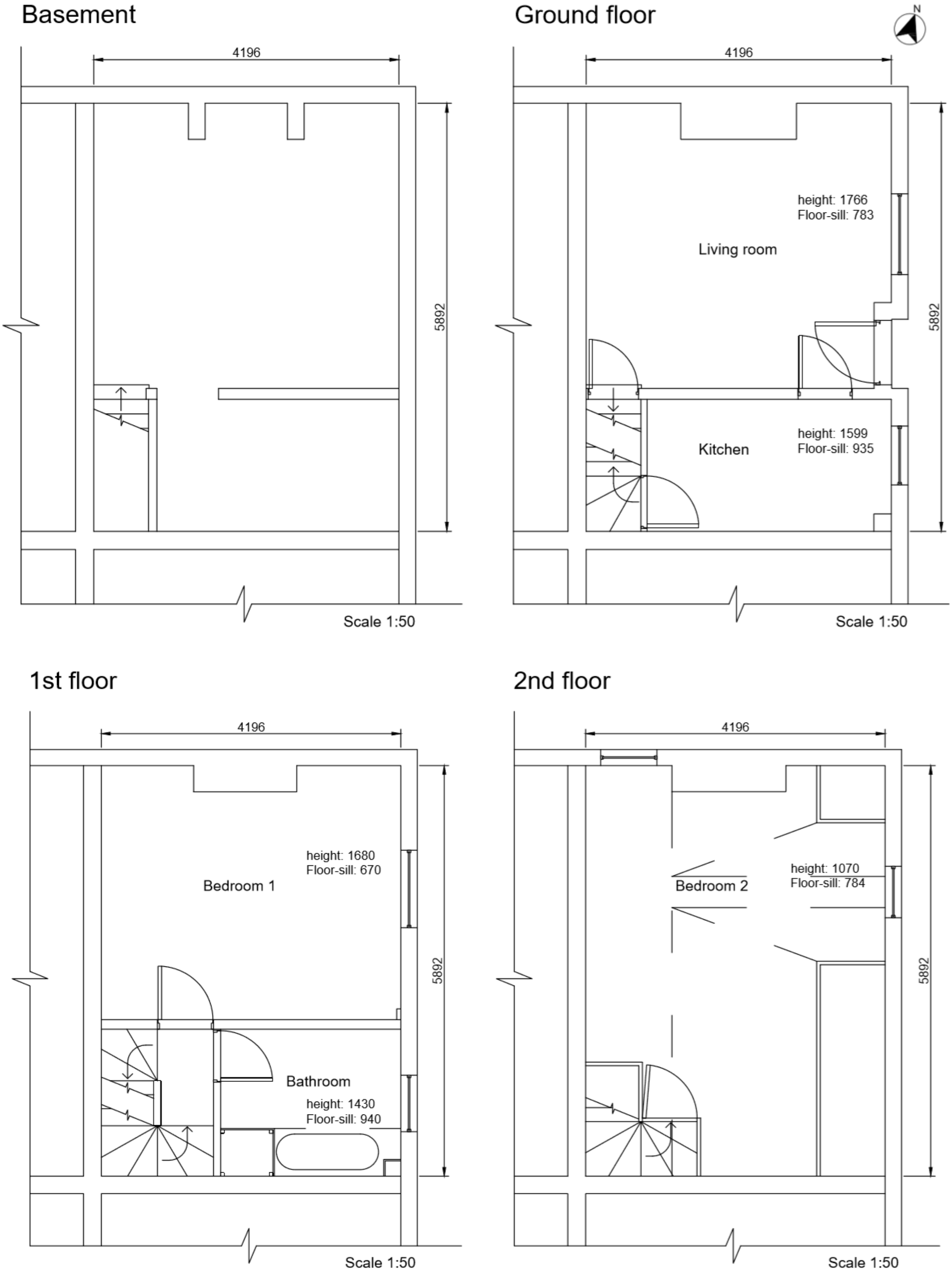

Figure 4-8 Plan of Test House C

4.6 External conditions data collection

Weather data was recorded from the roof of the Rose Bowl (53.802856, -1.547992), a high-rise building located on the Leeds Beckett University City Campus. Sensors were positioned such that environmental data measurement was unimpeded except for wind, which experienced partial sheltering from neighbouring buildings. The wind speed data gathered was enough for present analysis purposes, as wind data is used only as a reference for local conditions and not directly applied due to the significance of sheltering effects local to the test properties. Table 4-6 describes the parameters measured by the weather station with relevant accuracies and operating range.

Table 4-6 Measurement Parameters

Environmental Parameter	Unit	Range	Accuracy	Resolution
Barometric Pressure	hPa	600 to 1100	±0.5 at 0 to 30°C ±1.0 at -52 to 60°C	0.1
Wind Speed	m/s	0 to 60	±3% at 10m/s	0.1
Wind Direction	°	0 to 360	±3.0 at 10m/s	1.0
Rainfall	mm/h	0 to 200	>5%	0.1
Air Temperature	°C	-52 to 60	±0.3	0.1
Relative Humidity	%	0 to 100	±3 at 0 to 90 %RH ±5 at 90 to 100 %RH	0.1
Solar Irradiance	W/m²	0 to 2000	5% at -10 to 40°C	0.1

Figure 4-9 illustrates the location of the weather station in a local context. The location was chosen for several reasons. Firstly, it marks a central geographical location between the Test Houses, offering a representative point of data capture for all tests. Secondly, the location ensures that data collection and recovery is simple and reliable, with no risk of damage or interference from external sources. Finally, the location allowed constant power supply ensuring no data loss. Data were logged at 10-minute intervals with downloads occurring weekly. Linear interpolation between sequential data points was applied where conversion to 1-minute intervals was required. The data were compared with external temperature data logged at each of the Test Houses to evaluate comparability and it was found that the variance was insignificant, thus the weather station data are used for all three Test Houses.

Figure 4-9 Installed weather station (Left) with city centre location marked by red cross (Right)

5 Building Performance Evaluation Tests

This section presents the main findings from the BPE tests undertaken and evaluates how TIWI retrofits may improve the thermal performance of dwellings compared to conventional IWI retrofits. The detailed method and results for each test can be found in Annex B.

5.1 Impact of TIWI on Airtightness

Previous research has shown that retrofits can substantially improve airtightness, i.e. have a secondary benefit of reducing ventilation heat loss (Innovate UK, 2016). Specifically, research has shown that retrofits including IWI can reduce leakiness by between 8% and 61% depending on the amount of other work also being undertaken (Gorse et al., 2017).

In this research, before and after blower door tests were undertaken in accordance with Airtightness Testing and Measurement Association, Technical Standard L1A, Measuring Air Permeability of Building Envelopes (Dwellings) (ATTMA, 2010). Performing a blower door test is the approved method for ascertaining the airtightness of a dwelling in the Building Regulations 2010 Approved Document L1A (for new-build dwellings). Approved Document L1B (for existing dwellings) does not specify an airtightness test methodology only stating that "reasonable provision should be made to reduce unwanted air leakage through new envelope parts" (NBS, 2010b; NBS, 2010c; NBS, 2010a).

Figure 5-1 illustrates that the IWI and TIWI installed in the Test Houses had no measurable impact on infiltration rates. Blower door and CO_2 decay tests suggest that unregulated infiltration rates in Test Houses A and B were particularly poor; roughly double the leakiness of new build homes (21 and 18 $m^3/h.m^2$ respectively), while Test House C was roughly comparable with a new build (11 $m^3/h.m^2$).

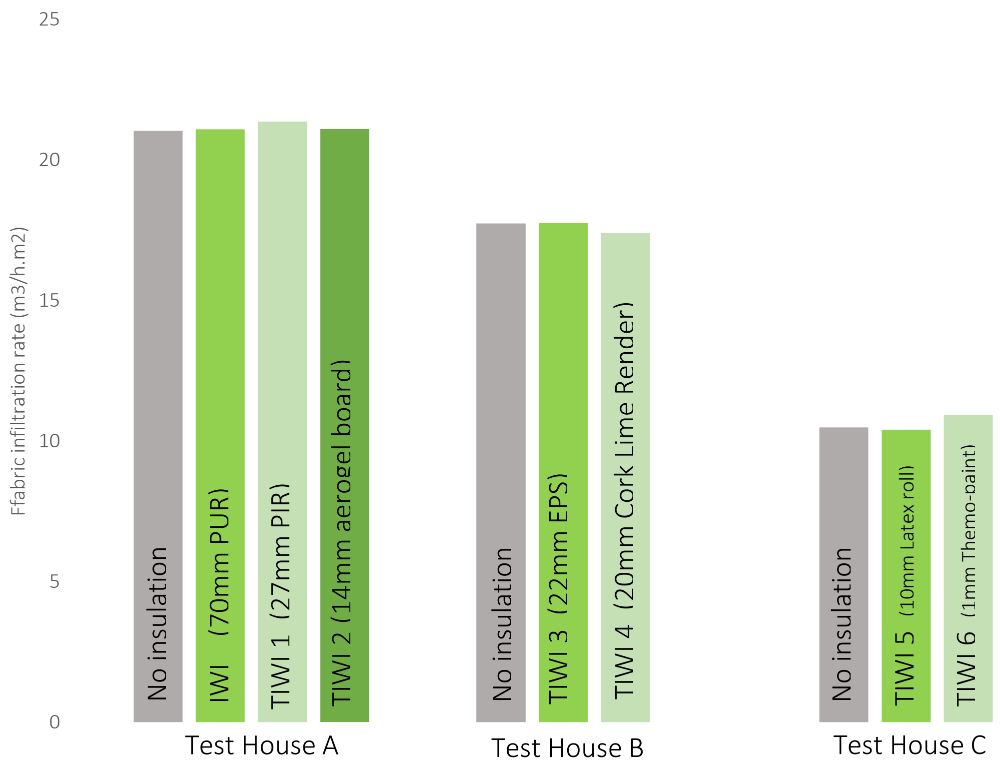

Figure 5-1 Impact of TIWI and IWI on dwelling airtightness

It is important to note that in each case wet plaster had been applied directly on top of the solid brick and so this result may not be repeatable in all solid wall UK homes which may have plasterboard or lath and plaster on battens. The findings imply that the heat loss savings achieved by TIWI and IWI will be conductive, i.e. convective heat loss may be unaffected if infiltration rates are unchanged. Additionally, since TIWI appeared to have no impact on airtightness in any of the Test Houses it is not likely to adversely impact indoor air quality via reduced ventilation rates. Moreover, it was observed that cellar doors and the suspended timber ground floor were responsible for most of the air leakage which also has implications for whole house retrofits.

5.2 Impact of TIWI on U-values

To measure the improvement in U-values that each IWI and TIWI achieved, *in situ* U-value and R-value measurements were undertaken in accordance with ISO 9869 (BSI, 2014)derived from measurements of heat flux density (using heat flux plates (HFPs) and the measured air temperature difference between the internal and external environments (ΔT). TIWI made substantial reductions to the wall U-values measured; an overview of the U-values achieved is shown in Table 5-1. There was no notable performance gap for any of the TIWI except for TIWI 4 which was thought to be due to uncertainties around the thickness of the product that was applied.

Table 5-1 Influence of insulation on wall thermal performance

	Insulation	Insulation Material	Insulation Thickness (mm)	Thermal Conductivity of insulation λ (W/mK)	Thermal Resistance of insulated wall R-value (m^2K/W)	Measured U-value of baseline wall (W/m^2K)	Measured U-value of insulated wall (W/m^2K)	Target U-value (W/m^2K)	U-value reduction
Test House A	IWI	PUR	70	0.021	3.49	2.11	0.30	0.31	85%
	TIWI 1	PIR	27	0.023	1.25	2.11	0.78	0.74	63%
	TIWI 2	Aerogel board	14	0.015	1.23	2.11	0.76	0.76	64%
Test House B	TIWI 3	EPS	22	0.040	1.03	2.01	0.98	0.98	49%
	TIWI 4	Cork render	20‡‡	0.037	0.93	2.01	1.36	1.06	32%
Test House C	TIWI 5	Latex rolls	10	0.052	0.68	2.10	1.30	1.49	38%
	TIWI 6	Thermo-paint	1*	0.047	0.50	2.10	1.25	n/a	n/a

Substantial U-value reductions of between 32% and 63% were achieved for TIWI and 85% for IWI. As can be seen, the law of diminishing returns was observed which supports the theory that the initial thin levels of insulation are proportionally the most effective and that increasing insulation thickness yields progressively smaller savings. For example, despite the insulating component of the conventional IWI being almost 4 times as thick as that of TIWI 1 and both having similar λ values (0.020 W/mK and 0.022 W/mK respectively), it only resulted in an additional 22% extra reduction in U-value. The law of diminishing returns is illustrated by the non-linear trend seen in Figure 5-2.

‡‡ Due to application method, exact thickness is uncertain

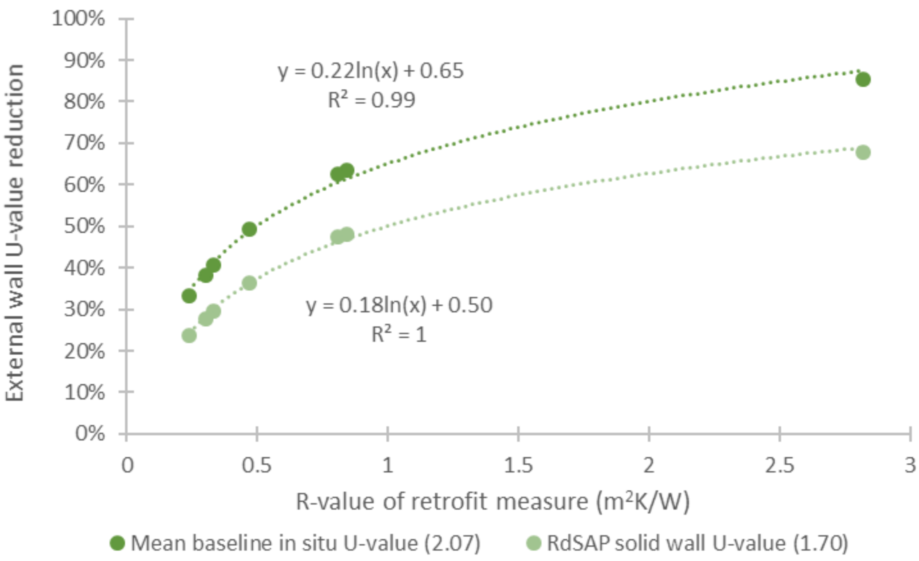

Figure 5-2 Measured R-value increase of insulation and measured reduction in external wall U-value applied to the mean measured baseline U-value of the three test walls and the RdSAP solid brick wall U-value

Figure 5-2 shows that in the case of the external walls measured in this project, doubling the R-value of insulation applied to them only results in an additional 15% reduction in U-value. This falls to approximately 12% if the RdSAP baseline is used. Thus, an initial increase in R-value to 0.5m²K/W was enough to reduce the *in situ* U-value by up to 50%.

In addition, it is interesting to note that the measured U-values of the base case walls (mean of 2.07 W/m^{2}K) were worse than the U-value of 1.70 W/m^{2}K assumed for solid walls in the Government's current modelling package, the Standard Assessment Procedure (SAP). This means that in these solid wall homes SAP is under predicting savings that the IWI and TIWI could achieve, as highlighted in Figure 5-3.

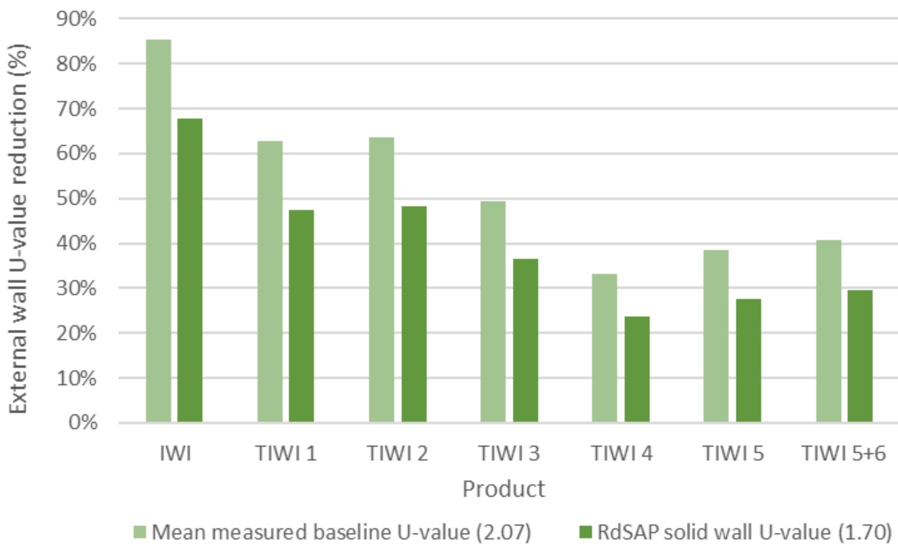

Figure 5-3 Percentage reduction in external wall U-value resulting from the application of each product to external walls with different baseline U-values

The airspace between an insulation board and the original wall surface was observed to result in uncertainty when calculating target retrofit U-values. An airspace narrower than specified can result in underperformance, which is especially true of products with a low R-value as shown in Figure 5-4.

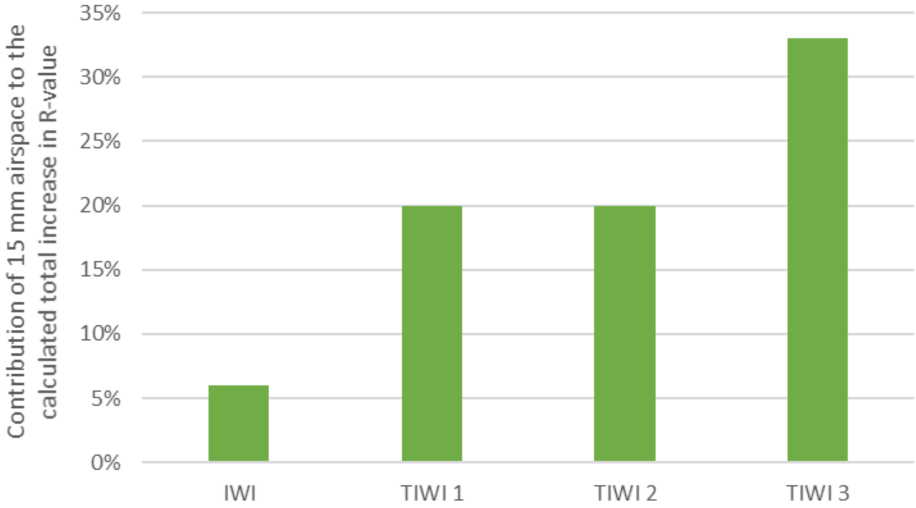

Figure 5-4 Contribution of a 15 mm airspace between the insulation and existing wall to the calculated total increase in R-value of IWI and TIWI 1 – TIWI 3

5.3 Impact of TIWI on Whole House Heat Loss (HTC)

Coheating tests were undertaken according to the Leeds Beckett University's (LBU's) Whole House Heat Loss Test Method (Johnston et al., 2013) to derive the heat transfer coefficient (HTC) before and after the retrofits took place; this method is widely adopted in the UK and has an uncertainty of between 8% and 10% (Jack et al., 2018). Reductions in measured HTC ranged from 13% to 18%, depending on the improvement in thermal resistance of the wall. Similarly, the proportion of the external wall that was insulated also directly influenced the savings achieved, as summarised in Table 5-2. Results shown for TIWI 6 are presented though this was applied on top of TIWI 5 and so it takes this as its base case.

Table 5-2 HTC reductions resulting from retrofits

	Insulation	Insulation Material	Thermal Resistance of insulated wall R-value (m^2K/W)	Measured U-value of insulated wall (W/m^2K)	Insulated wall area	HTC before retrofit (W/K)	HTC after retrofit (W/K)	HTC reduction
Test House A	IWI	PUR	3.49	0.30	23%	205	168	18%
	TIWI 1	PIR	1.25	0.78	23%	205	175	15%
	TIWI 2	Aerogel boards	1.23	0.76	23%	205	178	13%
Test House B	TIWI 3	EPS	0.97	1.03	19%	236	201	15%[§§]
	TIWI 4	Cork render	0.73	1.36	19%	236	196	17%[***]
Test House C	TIWI 5	Latex rolls	0.68	1.30	32%	177	160	10%
	TIWI 6	Thermo-reflective paint	0.50	1.25	38%	160	149	7%[***]

§§ Statistical analysis and disaggregation of HTC gives low confidence in measured result partly due to warm external conditions during testing

*** Thickness of applied product is uncertain

As illustrated in Figure 5-5 the absolute savings that were achieved were also proportional to the thermal performance of the base case house and although conventional IWI may achieve marginally more savings, it is clear that TIWI substantially reduces the space heating demand in solid wall homes.

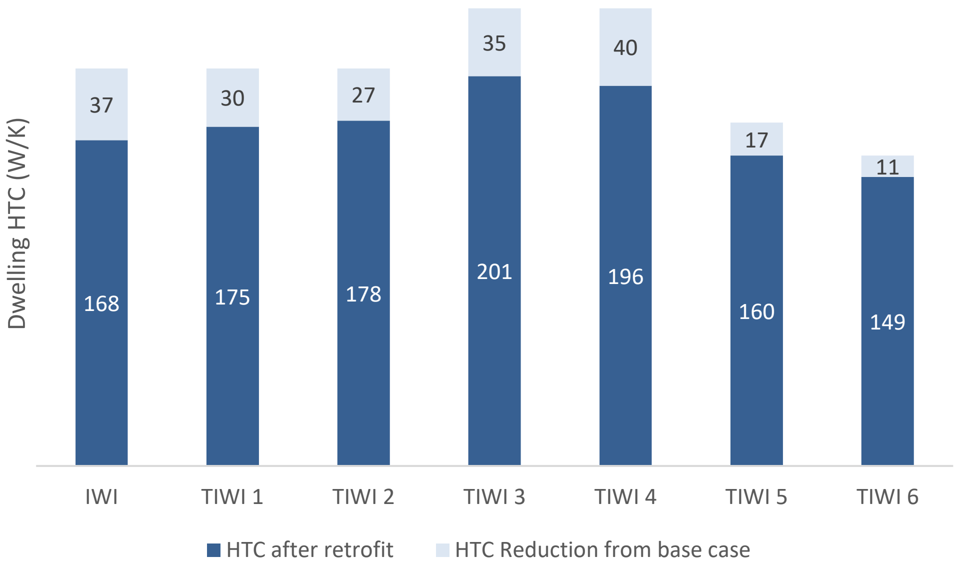

Figure 5-5 Overview of dwelling HTC before and after each retrofit

In summary, the IWI and TIWI was highly effective in reducing the U-value of solid walls resulting in meaningful reductions in household HTC, though the level of saving varies substantially. Determining which retrofit provides the best approach is determined by several factors including installation costs, site limitations, consumer preference, expected savings, payback times, breathability and risk of damp.

5.4 Impact of TIWI on Thermal Comfort

IWI potentially offers improvements to occupant thermal comfort via two processes; 1) cold internal surfaces which cause a cooling effect may be improved and 2) the rate at which heat is lost through the building fabric will be slowed, meaning the internal environment may retain heat for longer. This section explores these two issues and describes how changes to thermal comfort were measured in the Test Houses following the IWI and TIWI retrofits.

The findings of these tests are summarised here; the full results and test protocol are described in Annex B. The analysis has identified several findings, for example, despite using appropriately sized radiators, the houses do not achieve comfort when the SAP heating hours are used. Specifically, rooms on the ground floor were not able to reach the heating setpoint of 21°C pre-retrofit and rarely achieved this post retrofit though this is influenced in these homes by air exchanges with a basement. This finding further highlights the need to insulate these housing types, especially at floor level, to improve the comfort for occupants who may be living in cold homes.

The impact on comfort post retrofit is not so conclusive. A marginal improvement may have been achieved, however, despite the insulation, internal temperatures were still impacted by the external temperature, and a larger temperature difference during the measurement period has resulted in any potential improvement arising from the insulation product being undetectable. Unfavourable external conditions present a practical challenge for field tests and further research is needed to quantify the benefit to thermal comfort of IWI and TIWI.

5.5 Impact of TIWI on Heat Up and Cool Down Times

Another possible advantage for IWI and TIWI products is that post retrofit, homes may heat up more quickly and cool down more slowly, thus improving comfort for the occupant. To evaluate this, data from the simulated occupancy trials conducted in the test houses were analysed. The methodology and full results for evaluating the difference in heat up and cool down times in the test houses following the TIWI retrofits is described in Annex B.

The results indicated that neither IWI nor TIWI significantly improves heat up rates. TIWI may influence cool down rates, however, the effect is not substantial and appears to not be linked to the insulation's ability to reduce heat loss. Thermo-reflective paint appears to have the greatest impact, reducing temperature drops by 0.9°C over a single evening cool down. However, uncertainty is very high and some TIWI were found to accelerate cool down rates, perhaps because thermal mass was behind the insulation, or have no effect at all. More data collection is needed to validate the cool down modelled predictions. The observations made regarding cooling down should not be used to substantiate performance benefits as the tests are not conclusive.

5.6 Room in Roof TIWI retrofit

An additional test to investigate the effectiveness of TIWI as over boarding for a room in roof (RiR) was also undertaken on a separate Test House (Test House D). This supplementary investigation found that a RiR retrofit with TIWI could result in a 50% improvement in wall and roof U-values and reduce dwelling HTC by 20%. It also compared conventional RiR insulation (between rafters) with over boarding to TIWI and concluded that:

- RiR TIWI could deliver similar fabric heat loss reductions to solid wall TIWI for dwellings with a RiR. It is arguably a less disruptive retrofit method than solid wall retrofit as it involves work in fewer rooms of a house and many of the obstacles to solid wall retrofit are not present in a RiR (e.g. fireplaces, boilers, coving, telephone sockets, thermostats, etc.).
- Although TIWI does not deliver the same reduction in fabric heat loss as a conventional RiR retrofit, the cost savings attributable to specification, installation and material make it a worthwhile option to consider.
- No performance gap was measured for any of the retrofit products when comparing their measured and predicted U-value. However, conventional RiR retrofits would benefit from a laminated insulation over boarding finish (instead of plasterboard) as this would reduce thermal bridging through structural timbers.

6 Energy and Hygrothermal Simulations

This section presents the findings and implications for TIWI on thermal bridging when installation practice varies, including scenarios where insulation to window reveals is omitted. It also indicates how TIWI may affect surface and interstitial condensation risk and moisture accumulation in solid walls. Finally, it presents the findings from a range of Dynamic Thermal Simulation (DTS) scenarios which identify the improvements in thermal performance and comfort that may be experienced when different TIWI retrofits take place on different types of dwelling.

6.1 Modelling Thermal Bridging at Junctions following TIWI Retrofits

To investigate how thermal bridging is affected by TIWI, thermal models were created using Test House A as the base case. Each TIWI and IWI was modelled in turn with and without reveals and party walls insulated. TRISCO was used to model 3D steady state heat transfer for junctions of the building fabric, to calculate values for linear thermal bridging (ψ values) and assess the risk of condensation formation at these junctions using temperature factors (f_{Rsi}). The method and protocol for the simulations and the full results are presented in Annex C, and the main findings are discussed here.

Prior to the retrofits, intermediate floors and windowsills and jambs were identified as having a condensation risk. Applying IWI and TIWI to the external walls increased this risk where reveals were not also insulated. Insulating reveals removed the risk. Thermal bridging and condensation risk were generally less extreme when TIWI, which has lower thermal resistance, was used.

Additionally, decorative coving below intermediate floors, which was not an area of condensation risk prior to retrofits, presented a condensation risk following all TIWI and IWI retrofits and so may in all cases need to be removed before retrofit. The risk was most pronounced in IWI though became less extreme in TIWI with lower levels of thermal resistance. This has implications for the costs of IWI and TIWI retrofits since it is not known how many solid wall homes may have decorative coving. Conversely, in the case of ground floor junctions, in all instances applying IWI or TIWI to the external wall will reduce the risk of condensation or at least not worsen the risk substantially.

In the case of partition and party walls, insulating only one side will cause increased risk of condensation on the uninsulated adjacent side, though the effect is less pronounced for TIWI. This is a concern where the adjacent room is subject to high levels of relative humidity, and for party walls if any damage manifests following the retrofit of a neighbouring property. The situation is complicated by the fact that often the risk of condensation in the uninsulated base case condition may have already been of concern.

Thus, in IWI and TIWI retrofits, junctions should be adequately insulated, or condensation risk will increase. Where this does not take place, if TIWI is used the increase in risk will be lower than if conventional IWI is used.

6.2 Comparing Measured Condensation Risk with Hygrothermal Simulations

WUFI Pro simulations were undertaken in accordance with BS EN 15026 (BSI, 2007) on each of the TIWI installed on a 9-inch solid brick wall. These compared the water content build up post retrofit compared to the base case wall as well as specifically looking at water content at the inner masonry leaf behind the insulation and at joist ends to evaluate whether the risk of rot would be increased. The potential for frost damage was also investigated. The full simulations and results are provided in Annex C.

6.2.1 Water content following IWI and TIWI retrofits

Table 6-1 shows insulation caused water content to fall more slowly than the base case uninsulated wall, potentially increasing the risk of mould and rot. This was especially the case for IWI and for TIWI with greater thermal resistance, for which moisture levels remained relatively high. In all TIWI retrofits the moisture content was substantially higher than the base case though lower than in the IWI retrofit.

Table 6-1 Water content at start and end of simulation

	Total water content (kg/m²)	Base Case	IWI	TIWI 1	TIWI 2	TIWI 3	TIWI 4	TIWI 5	TIWI 6
Total Wall	Start	4.67	4.76	4.77	4.83	4.78	5.42	4.67	4.67
	End	2.57	4.58	3.94	3.31	3.62	3.33	2.79	2.62
	Reduction	45%	4%	17%	31%	24%	39%	40%	44%
Inner brick leaf	Start	18	18	18	18	18	18	18	18
	End	7.42	19.04	14.98	10.57	12.84	8.7	8.43	7.65
	Reduction	59%	**-6%**	17%	41%	29%	52%	53%	58%

More noteworthy for the inner leaf, IWI is expected to increase the moisture content over the three-year simulation period, identified in bold as a negative value in Table 6-1. In all other cases moisture content falls. This implies that there could be an increased risk of moisture build up on the inner brick leaf in IWI retrofits, something that may not occur for TIWI retrofits. It is worth noting however that the rate of drying was slowed (therefore risk of moisture problems increased) in all the TIWI retrofits, and the extent to which the drying was slowed down was relative to insulating properties of the materials.

6.2.2 Risk of mould and rot at joist ends following IWI and TIWI retrofits

Relative humidity over 80% allows mould growth to occur. Dry rot within timber favours temperatures over 23°C. In hygrothermal simulations a temperature of 20°C is used as a threshold of risk. Temperature and humidity measurements were taken at the boundary at the mortar layer between outer and inner leaf (this is the expected location of joist ends within the wall). Table 6-2 summarises the number of 1-hour intervals during which conditions are conducive to mould or rot growth at the location of joist ends. All interventions result in an elevated duration of risk to the joists, though most severe for the thicker conventional IWI system. More vapour open (breathable) systems pose a shorter duration of risk conditions. This outcome is likely due to two factors: reduced drying potential due to the IWI reducing heat flow into the wall, and increased resistance to water vapour escaping from the internal face of the wall due to IWI.

Table 6-2 Duration of mould and rot risk conditions at joist end locations

	Hours over 80 % RH	of which over 20 °C	% of time at risk
Base Case	4523	40	0.2%
IWI	22218	2965	11.3%
TIWI 1	17869	1398	5.3%
TIWI 2	15509	742	2.8%
TIWI 3	16821	1140	4.3%
TIWI 4	10253	190	0.7%
TIWI 5	9275	147	0.6%
TIWI 6	4888	61	0.2%

6.2.3 Risk of frost damage following IWI and TIWI retrofits

The reduced fabric temperatures that occur within the brickwork when IWI is applied can potentially lead to frost damage in the outer layers of the brickwork due to freeze-thaw cycles. A layer of the external leaf of brickwork from 5.5mm to 11mm from the external surface was monitored for water content. Temperature at the 5.5mm boundary was also recorded. Since water expands in volume by 10% when it freezes, the brick wall structure would potentially be at risk of frost damage if the water content of the monitored layer reaches 90% of the brick porosity whilst the temperature of the brick fell to 0°C or lower. However, in all cases the water content did not reach the threshold of 90% that could lead to frost damage. It is not therefore likely that either IWI or TIWI retrofits will lead to frost damage of masonry walls.

6.3 Predicting Thermal Performance of TIWI using Dynamic Thermal Simulation

Since field trials only generate data for specific case studies, it can be difficult to extrapolate findings. An extensive modelling programme was therefore developed to predict what the broader impact of TIWI could be for the UK. The Test House were used to develop calibrated Dynamic Thermal Simulation (DTS) models and the method and findings are presented in Annex C. From these models it was possible to predict what the impact of TIWI could be on a range of key performance indicators and under a range of different conditions including overheating as well as exploring potential impact on HTC, GHG emissions and fuel bill savings under SAP and extended occupancy conditions for homes. Furthermore, using representations of the architypes developed by the Building Research Establishment (BRE) to calculate the deemed scores in ECO3 for the different retrofits, it was possible to investigate how TIWI savings may translate to the UK housing stock.

6.3.1 TIWI impact on overheating and a warming climate

CIBSE's TM59 introduces a set of operating profiles that simulate the worst-case scenario of continual occupancy under average heatwave conditions and has been used to evaluate the influence that TIWI has on overheating risk. There is no risk of overheating in the Test Houses pre- or post- retrofit. However, using future climate scenarios for 2050 our models predict that solid wall homes may overheat, although there is a potential TIWI can roughly half the extent of overheating that may occur according to both TM59 overheating criteria:

A) that homes can only be 3°C warmer than the external temperature for 3% of the time in summer; and
B) that in the evenings, bedrooms don't exceed 26°C for more than 1% of time.

6.3.2 TIWI impact on modelled HTC, annual space heating, GHG and fuel bill savings

HTC, annual space heating demand, GHG emissions and fuel bill savings in homes are intrinsically linked. These are influenced by the efficiency of the heating system in the home, the fuel use, and the heating profiles for the dwelling, as well as the carbon density and cost of fuel. The impact that TIWI and IWI have on these metrics has been assessed through DTS and is described in Annex C. Here we present an overview of the findings.

The columns in Figure 6-1 show the average heating bill cost saving modelled when each insulation was applied to each of the Test Houses in the field trials. In addition, the coloured dots show the actual improvement in each Test House. As can be seen, since Test House C had a larger proportion of external wall insulated it achieved much higher absolute savings.

TIWI 7 represents a retrofit where both TIWI 5 and 6 are applied together to the external walls though the addition of TIWI 6 makes only a marginal difference. In general, TIWI achieved fewer savings than IWI since the reductions are proportional to the improvement they provide to HTC in the models.

The variability in savings achieved across all the houses and retrofits is large: £41 to £262 per year (excluding TIWI 6 and 7). This highlights how complex the retrofit market is and how sensitive fuel bill savings are to the dwelling and retrofit characteristics. To determine the savings that may be achieved nationally by IWI or TIWI a detailed understanding is required of suitable external wall area of those solid wall homes yet to be insulated and what materials may be used. Further research may be undertaken to understand if TIWI and IWI should be focussed only on homes which have a minimum proportion of the heat loss area that can be insulated.

Also shown in Figure 6-1 is a summary of how the annual fuel bill savings differ when different occupancy profiles are used, assuming a gas boiler is installed. SAP assumed heating profiles predicts fewer savings compared to the extended occupancy assumptions. If savings are dependent on occupant heating patterns this has implications for energy policy. Currently, ECO targets vulnerable households, mainly the fuel poor, who may have extended occupancy profiles, similar to those shown in this study, however RdSAP uses average occupancy profiles. Thus, more research on the heating profiles of vulnerable groups may be required.

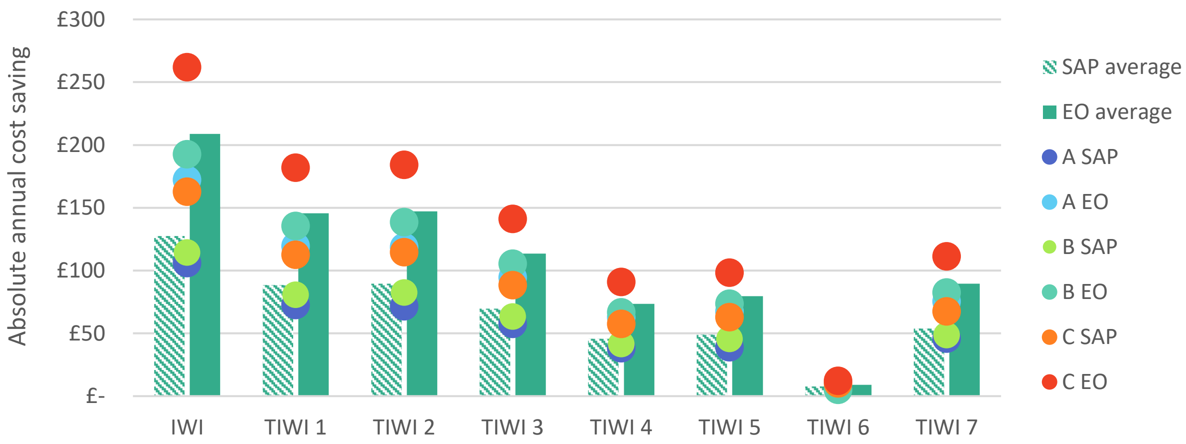

Figure 6-1 Summary of modelled absolute annual cost savings for all Test Houses, showing Test House C under extended occupancy (EO) (red dots) has highest savings due to a larger insulated area than the other homes and more heating hours than SAP

Calibrated DTS model outputs for HTC, fuel bill and GHG emission reductions for each of the TIWI and IWI are shown in Table 6-3. Whilst relatively substantial savings are predicted to HTC, owing to the range of energy use (electricity, heating and cooking) in homes, this translates to modest savings in overall GHG emission reductions. Products with lower thermal conductivity achieve proportionally higher savings per mm, and only TIWI 1 was seen to be more cost effective (per mm) than IWI at reducing fuel bills, though this may change if TIWI products become mainstream solutions and their installation costs fall.

Table 6-3 Average calibrated DTS model outputs

		Thickness	HTC reduction	HTC reduction per mm	Fuel bill savings	GHG reduction	Installation costs (£ per m²)	Installation cost per m² per £1 fuel bill saving
IWI	PUR	70	33%	0.47%	£128	4.6%	£157.10	£1.23
TIWI1	PIR	27	23%	0.85%	£89	3.2%	£101.98	£1.15
TIWI2	Aerogel	14	23%	1.64%	£89	3.3%	£149.94	£1.68
TIWI3	EPS	22	18%	0.82%	£70	2.5%	£113.29	£1.62
TIWI4	Cork render	20	11%	0.55%	£46	1.7%	£106.98	£2.33
TIWI5	Latex rolls	10	13%	1.30%	£49	1.4%	£95.58	£1.95
TIWI6	Thermo-paint	1	3%	3.00%	£10	0.4%	£30.27	£3.03

6.3.3 Modelling the influence of TIWI on cool down rates

The field trials found that the IWI and TIWI made only marginal change in cool down times, and the data for these were not considered reliable due to the limitations on conditions posed by field trials including lack of control over external conditions, lack of repeatability and sensitivity of measuring equipment. An attempt to model changes in cool down temperatures in a controlled virtual scenario has therefore been made and is described in full in Annex C.

The simulations found that the retrofits reduced the cool down rates, although these were again marginal; an example of these are shown in Figure 6-2. The implication of this is that comfort may be maintained for longer in dwellings.

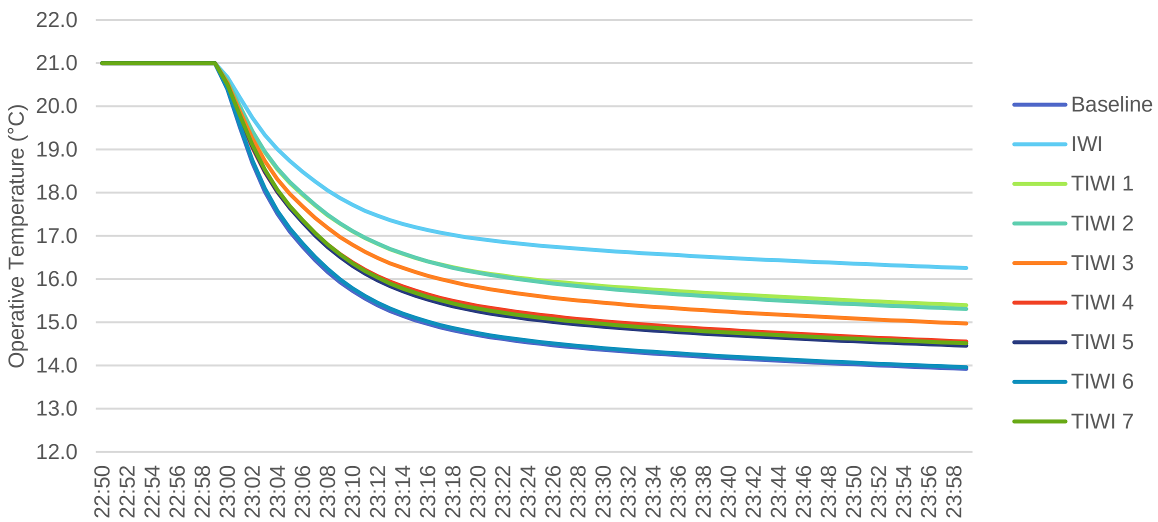

Figure 6-2 Modelled minute data for time taken to reach heating setpoint in the lounge of Test House C on 23rd February

In addition, it is possible that dwelling temperature may not drop as substantially between heating periods potentially reducing the ΔT at the beginning of the next heating period between the starting temperature and the setpoint temperature. This is illustrated in Figure 6-3 and means retrofitted dwellings are likely to reach slightly higher operative temperatures due to the increased surface temperature of the external walls. This also indicates that there is an additional mechanism responsible for reducing heating demand in dwellings in addition to the steady state conductive heat loss reductions predicted by EPCs.

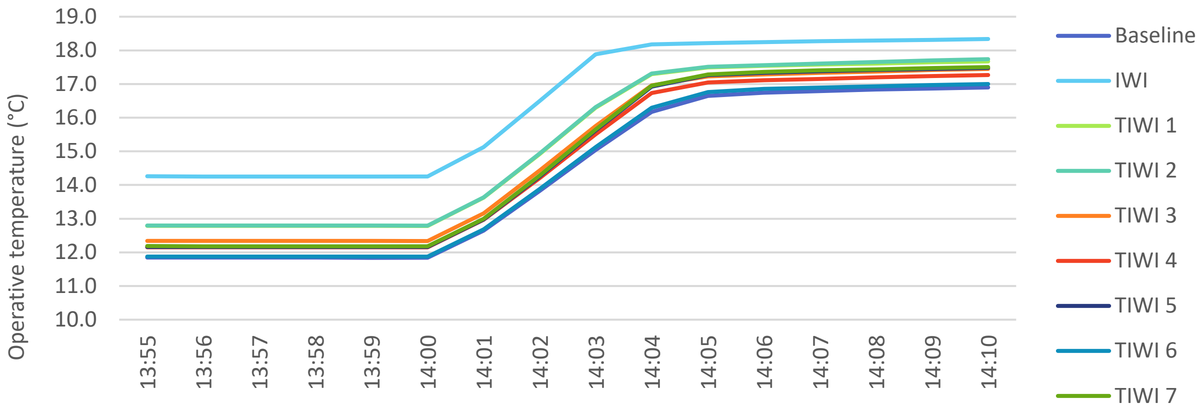

Figure 6-3 Modelled heat-up data for the operative temperature in the lounge of Test house C on 23rd February

6.3.4 Impact of TIWI on homes of different UK archetypes

Annex C also describes the extensive modelling undertaken on the impact of TIWI on the fuel bill savings that may be expected in a range of UK housing archetypes, based on the models developed to generate deemed scores for ECO3. The work also considers what the impact of TIWI would be on cavity wall homes with and without cavity wall insulation (CWI), as well as considering how varying states of glazing area and background ventilation will impact on projected savings. Although TIWI is proposed as a solution to solid wall homes, it may also be installed on hard to treat uninsulated cavity walled homes. Also, it may be possible that insulated cavity walls may need an additional improvement if higher EPC bands are required and so could also profit from TIWI.

This study identified that if TIWI was installed on solid wall homes, the average saving to HTC could be 17%. For uninsulated cavity wall dwellings, the average could be 13%. The savings for the insulated cavity wall dwellings were likely to be negligible however, with an average of 3%. This indicates that TIWI could be a realistic solution for treating non-standard cavity walled homes which can be more expensive to install than standard cavities (EST, 2019) or where cavity wall insulation is not feasible, for example in high exposure zones. Table 6-4 summarises these findings and highlights that IWI and TIWI retrofit savings depend on the base case dwelling circumstances.

Table 6-4 Average percentage reduction in annual space heating energy following retrofit

	Modelled savings achieved by IWI			Modelled average savings achieved by TIWI 1 - 5		
Assuming 12 ach	10% glazing (low)	20% glazing (medium)	50% glazing (high)	10% glazing (low)	20% glazing (medium)	50% glazing (high)
Solid wall	56.81%	53.75%	38.61%	26.47%	25.31%	18.53%
Uninsulated Cavity wall	51.53%	48.26%	33.17%	21.74%	20.53%	14.18%
	Modelled savings achieved by IWI			Modelled average savings achieved by TIWI 1 - 5		
Assuming 20% glazing	9ach (low)	12ach (medium)	18ach (high)	9ach (low)	12ach (medium)	18ach (high)
Solid wall	58.80%	53.75%	45.34%	27.69%	25.31%	21.35%
Uninsulated Cavity wall	53.16%	48.26%	39.79%	22.80%	20.53%	16.92%

The results suggest that the average impact of installing TIWI could be a reduction in HTC of 11%, however this varies according to how much glazing is present for example ranging from 5% savings in dwellings with 80% glazing, up to 15% savings for dwellings with 10% glazing. IWI savings would be slightly higher; on average 13% per annum, though again this would range from only 6% savings in dwellings with 80% glazing, up to 19% savings for dwellings with 10% glazing. Available wall space suitable for insulation is directly proportional to realised savings. It may therefore be considered that alternative insulation strategies should be adopted for house types with small areas of external wall such as back to back, mid terraces and flats.

The influence of background ventilation was also investigated. Homes with poor levels of airtightness benefitted less than more airtight homes showing that, for TIWI 2 for example, the reduction in heating energy demand for the interquartile range was 37%-41% when the infiltration rate was set at 9 AC/H, compared with an interquartile range of 25%-29% when set at 18 AC/H.

6.3.1 Impact of TIWI on UK housing stock

The outputs for the DTS models were used in conjunction with English Housing Survey (EHS) data to evaluate the expected benefits of TIWI for different house types in the UK. The assumptions used in this assessment are presented in Annex C. Using the data from the DTS models, it is possible to predict the cumulative benefit of each retrofit if all solid walls were to have wall insulation installed in the UK, assuming 24.6% of homes have solid walls (taken only from the EHS). Of the 27.2 million homes in the UK (ONS, 2018), this would equate to 6.7 million solid wall homes. As can be seen in Figure 6-4, although detached properties provided the greatest individual benefit from the wall retrofits, since they have the largest wall area, on a national scale the greatest savings would be achieved from semi-detached, mid terraces and flats, owing to their abundance.

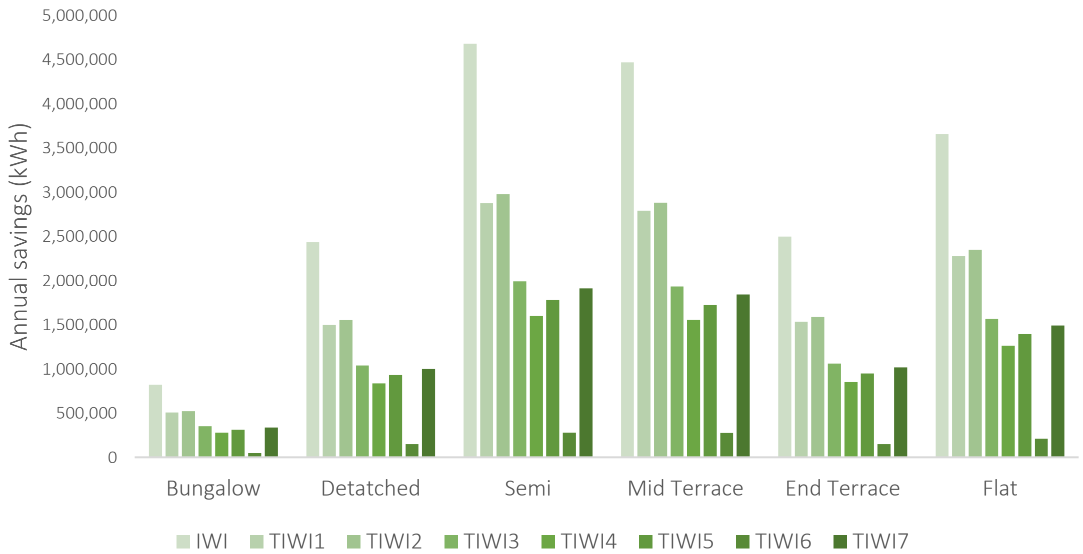

Figure 6-4 Predicted national impact of internal wall insulation per house type if all solid wall homes were retrofitted

7 Laboratory Investigations into IWI and TIWI Moisture Risks

To support the social science investigations, modelling and field work into the benefits, risks and opportunities for TIWI, laboratory research was also undertaken to quantify what risks may be introduced into homes that have TIWI and IWI retrofits. To answer these aims, test walls were built in breathable and non-breathable plaster to replicate the walls found at the field work Test Houses. These were equipped with thermocouples and heat flux sensors and exposed to accelerated weathering to simulate UK rain conditions. An attempt was made to measure moisture movement through the bricks during the wetting cycles, however, due to excessive salt accumulation, this was not possible.

The U-value, surface condensation risk and interstitial condensation risk was monitored in quasi steady state conditions in the dry and wet phase. The water accumulation following the wetting was also analysed by taking core samples from each wall. Generally, wetter bricks had higher U-values and the impact of rain on brick thermal performance may therefore warrant further study.

Surface condensation risk was shown to be reduced by similar degrees following the installation of both TIWI and IWI. However, interstitial condensation risk was only somewhat introduced when TIWI was installed but substantially introduced when IWI was installed.

Moisture content was calculated using core samples of the walls and it was observed that for the internal brick, in 5 out of 7 cases, the walls with gypsum plaster tended to result in a wetter inner brick than the breathable solutions after the wetting cycle, regardless of if a TIWI or IWI was installed.

8 Policy Implications

The research has attempted to answer what role TIWI may have in the future retrofit industry and domestic energy efficiency policy in the UK. Table 8-1 summarises findings that may be most useful for policy decision makers and the following sections discuss the implications of the findings. The final section provides several policy recommendations.

Table 8-1 Summary of TIWI findings

Insulation	Material	Thickness (mm)	U-value reduction	HTC reduction	Insulated wall area	Cost per m^2	Modelled annual fuel bill savings[†††]	RdSAP point savings[‡‡‡]	% of time at risk of damp
IWI	PUR	70	85%	18%	23%	£157	£128	9.78	11.3%
TIWI 1	PIR	27	63%	15%	23%	£102	£89	6.79	5.3%
TIWI 2	Aerogel	14	64%	13%	23%	£150	£89	6.92	2.8%
TIWI 3	EPS	22	49%	15%	19%	£113	£70	5.32	4.3%
TIWI 4	Cork render	20[§§§]	32%	17%	19%	£107	£46	3.46	0.7%
TIWI 5	Latex rolls	10	38%	19%	32%	£96	£49	3.80	0.6%
TIWI 6	Thermo-paint	1[§§§]	n/a	n/a	38%	£30	£10	0.61	0.2%

8.1 Optimum TIWI materials

A range of technologies has been assessed in this project, though more TIWI technologies are available, and more innovations may become available in the future. This report does not attempt to suggest which technology is superior but identifies the opportunities and limitations of each. Installers were comfortable with rigid board insulations since it closely aligns with existing practice, although it was acknowledged these were awkward to cut on site and manoeuvre, created excessive dust and waste and were not popular, especially where installers were forced to use the manufacturers' own fixing products rather than the conventional dot and dab approach. Render was equally familiar to the installers and quick to install, however, the need to return to apply a second coat negated any time and cost savings. The latex rolls created waste as per the rigid boards and required skilled workers to deal with detailing. All TIWI required additional decoration after installation, however, the render and thermo-reflective paint could conceivably be left as the finishing layer, which would save costs. Future products therefore should:

- Avoid excessive dust, waste and mess
- Avoid cutting onsite
- Avoid multiple visits
- Have conventional fixing systems
- Have a decorative finish
- Match skills of current installers

††† Assuming identical wall areas insulated

‡‡‡ Assuming a gas boiler in Test House C

§§§ Due to application method, exact thickness is uncertain

8.2 Optimum TIWI thickness

Several thicknesses of TIWI have been tested in this project and the law of diminishing returns suggests that TIWI may be more cost effective than IWI, i.e. additional savings from thicker insulation provides progressively fewer savings. However, the optimum thickness of insulation varies according to what material is used and the marginal cost of increasing the thickness of the insulation. As an illustration, in this research only 7 W/K additional savings in HTC were achieved by IWI compared to TIWI 1, meaning IWI achieved 18% reduction in HTC whilst TIWI 1 achieved 15%, i.e. over 83% of the retrofit benefit was delivered for half the thickness and two thirds of the cost. Understanding the relationship between cost and thermal performance is not clear, however, the cost of installation was mostly influenced by the method of application rather than the cost of the product (e.g. was only one visit needed and was additional decoration needed?). Having a range of options may be beneficial, and breathable solutions should be preferred regardless of thickness.

8.3 Reducing unintended consequences via TIWI

The research has shown that, if installed in accordance with best practice, IWI or TIWI retrofits are not likely to increase surface condensation risk in the retrofitted dwelling. However, IWI is likely to increase risk of rot to joist ends since moisture content may accumulate over several years - this may not occur with TIWI. Another issue of note is that neighbouring dwellings, uninsulated areas or uninsulated rooms divided by partitions may see their condensation risk increased, especially when returns are insulated. Installers have revealed that they cannot usually install IWI retrofits in accordance with best practice, and consider PAS guidance as "*irrelevant, unachievable and impractical*", not least as specific designs are seldom produced for details or complicated features. Thus, if policy's aim is to ensure additional risks are minimised in homes following retrofits, TIWI may be preferred over IWI.

8.4 TIWI role in GHG and EPC targets

Substantial improvements in space heating demand reduction have been observed following TIWI retrofits; 72% to 83% of the benefit of conventional IWI. However, domestic space heating contributes around half of a home's energy use and homes make up just 15% of the UK GHG emissions (BEIS, 2017). Given that only a proportion of the 6 to 8 million solid walled homes in the UK may be suitable for IWI retrofits, neither IWI nor TIWI are likely to achieve substantial moves towards national carbon budgets. However, they may both reduce heating demand by similar levels and improve EPCs by a similar degree.

8.5 TIWI potential to improve comfort and health outcomes

This research has found that it is probable that 'optimal' thermal comfort conditions may not always be achieved in solid walled homes without prolonged heating hours or radiators that have been sized to meet peak heating demands. Installing TIWI can increase thermal comfort, however, the overriding variable on thermal comfort even after retrofits take place is the external temperature. Retrofitting homes with TIWI or IWI may therefore not be enough to achieve comfort and a whole house approach is needed, specifically addressing drafts and ground floor insulation. No TIWI or IWI product showed a meaningful impact on thermal comfort nor the rate at which they heat up or cool down and therefore comfort was not materially affected by the marginal improvements in surface temperatures observed.

8.6 IWI & TIWI policy and practice

Installers tend to install IWI as part of other renovation works taking place in homes. Often TIWI is preferred over IWI as an alternative to standard plasterboards because it is easier to handle on site, takes up less space and is cheaper than IWI. Installers often avoid IWI retrofits funded via ECO3 due to additional administrative burdens and because there is insufficient finance provided to do a "good job". This means there are many solid wall homes that have had informal IWI retrofits, which reduces the remaining potential number of homes for IWI, although research is needed to understand the quantity and quality of these. Given that IWI is not popular, room in roof retrofits should be encouraged as these can be even more effective.

TIWI is a type of IWI and therefore supported in existing ECO3 policy. However, payments are made according to predicted RdSAP savings which therefore encourages retrofits of conventional IWI. Building regulations often reject TIWI on the grounds of not achieving limiting U-values quoted in Part L1B. This discourages any SWI from taking place in homes, especially those with small areas of external wall or large areas of glazing, such as mid terraces, back to backs and flats. This is despite these types being common solid walled homes in the UK and often occupied by the fuel poor. These act as barriers to TIWI retrofits, pushing them outside the ECO scheme. It is not known how many TIWI retrofits have taken place under ECO as opposed to IWI as reporting methods do not make the distinction.

Based on the analysis of the questionnaires, it was shown that acceptability and demand for retrofit measures can be directly linked to general awareness among householders, and awareness of IWI was found to be low. Based on the analysis of the historic surveys and feedback from installers, a whole house approach may not be achieved in IWI retrofits since there is insufficient finance to undertake all necessary remedial and additional measures. The modelling work has identified that the majority of solid walled homes in the UK have two or fewer external walls, and that these will not be predicted to provide a significant reduction in fuel bills in EPCs. It also identified that TIWI could provide substantial savings for hard to treat uninsulated cavity walls and insulated cavity walls where higher EPCs are needed. However, neither IWI or TIWI is currently identified as an EPC recommendation for cavity walled homes. Furthermore, the installer feedback identified that unreasonably high standards, lack of support from building control officers and high administrative burden of policy compliance is deterring installers from engaging in IWI and ECO.

Several findings from the installer interviews, laboratory investigations and modelling work also identified measures that could reduce the risk of unintended consequences of condensation risk, mould and timber rot at joist ends, including:

- Improve knowledge of the problems associated with reduced vs enhanced retrofits
- Discourage the practice of insulating party wall returns
- Provide incentives for the use of breathable IWI retrofit systems
- Remove minimum target U-value for IWI retrofits in ADL1B

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