Department for
Energy Security
& Net Zero

LEEDS BECKETT UNIVERSITY
LEEDS SUSTAINABILITY
INSTITUTE

DEEP Report 2.03

Case Study 56TR

October 2024

Prepared for DESNZ by

Professor David Glew, Leeds Beckett University (LBU)

LBU contributing authors (alphabetically):

Mark Collett
Dr Martin Fletcher
Dr Adam Hardy
Beth Jones
Dominic Miles-Shenton
Dr Kate Morland
Dr Jim Parker
Dr Kambiz Rakhshanbabanari
Dr Felix Thomas
Dr Christopher Tsang

Any enquiries regarding this publication should be sent to us at: EnergyResearch@energysecurity.gov.uk

Contents

Executive summary

56TR *is one of fifteen homes being retrofitted in the DEEP project. The case studies are being used to identify the performance of, and risks associated with, retrofitting solid walled homes as well as to evaluate the accuracy of retrofit models.*

In this case study the cumulative loft replacement, suspended floor, wall, and sloping ceiling retrofits were observed to reduce the home's heat transfer coefficient (HTC) by (82 ± 20) W/K, or (37 ± 9) %, according to coheating tests. The HTC reduction predicted by an Energy Performance Certificate (EPC) was 128 W/K (41 %). The predicted and measured percentage reductions may appear to be in reasonable agreement, though as found in other DEEP case studies, the absolute savings predicted were much more than were measured. This suggests that predicted paybacks from EPCs can be misleading where there is an incorrect EPC prediction for the starting condition of the home. Both models and measurements agree that the vast majority of the savings are achieved by the solid wall retrofits.

Investigations revealed that the accuracy of steady-state energy models, used to generate EPCs for the uninsulated home, could be improved when defaults for U-values, airtightness, and thermal bridging heat loss were replaced with measured and calculated values. However, replacing default data was less important in the retrofitted home where the default U-values more closely matched those that were measured. Regardless of which data inputs were used, the home was judged to have an EPC Band D pre-retrofit, improving to a Band C post-retrofit.

The case study further found that dynamic simulation models (DSM) predicted HTC values that were much lower than steady-state models and, in this instance, they aligned very well with the measured coheating test HTC. Interestingly, including the measured airtightness and U-values made no noticeable difference to how close the DSM HTC was to the coheating value, though including the calculated thermal bridging saw the prediction drift further away from the measured values by a small margin. These findings reaffirm that simplified energy models, including EPCs, which rely on default data, are not able to accurately predict retrofit savings or payback. Replacing defaults with measured or calculated values improves accuracy though does not resolve the problem. They also suggest that dynamic models may be more accurate, though more investigations into how models apply thermal bridging heat loss is needed.

Thermal bridging simulations undertaken for the case study home, found that heat loss via thermal bridges reduced from 50 W/K (17 %) to 21 W/K (11 %), mostly as a result of installing loft insulation behind a purlin to ensure a continuous layer from the loft to the sloping ceilings. The wall and floor retrofits marginally increased thermal bridging heat losses. The y-value of the uninsulated home was calculated to be 0.18 W/K, greater than the RdSAP default value. However, post-retrofit, the calculated y-value reduced to 0.07, suggesting that the application of y-value defaults may need revision to consider what insulation is present in homes.

57 % of junctions in the uninsulated home had a risk of condensation, with greatest risk in sloped ceiling. The retrofits, especially the internal wall insulation, reduced these, though a risk persisted at four junctions. Suspended floor risks were not remedied by the floor insulation, but were by the wall insulation, while risk at the solid floor junction was only removed by below damp-proof course insulation being added after the external wall insulation. The results suggest that uninsulated solid wall homes tend to overheat, and this can worsen after wall and loft retrofits. However, more research is needed to understand by how much risk may reduce from insulating ground floors and removing discontinuities in the home's insulation.

1 Introduction to 56TR

Case Study 56TR is a three-bedroom 1920s end-terrace in which a whole house retrofit was undertaken. The whole house retrofit was undertaken in stages, reflecting a piecemeal approach to retrofit, with stages comprising loft insulation, floor insulation, and wall insulation. A final retrofit stage was also undertaken to address the issues missed by the piecemeal retrofits – issues which should normally be addressed via a typical whole house approach. These issues included applying internal wall insulation (IWI) on the raked eaves (skeilings) and external and internal wall insulation (EWI & IWI) installed below the damp-proof course (DPC). The performance of each individual retrofit stage was assessed for airtightness, thermal performance, and moisture risk. This case study also provided the opportunity to investigate a hybrid approach to solid wall insulation (IWI installed at the front and back wall with EWI installed on the gable wall) and applying suspended floor insulation when only half the floor was suspended.

1.1 DEEP field trial objectives

56TR is one of fifteen DEEP case studies which, collectively, will attempt to investigate the research objectives listed in Table 1-1, though not all the objectives are addressed by each case study.

Table 1-1 DEEP research objectives

Objective	Rationale
Model input accuracy	Policy relies on models with known limitations; exploring inputs and model robustness will improve policy advice.
Unintended consequence	More retrofit scenarios need modelling to confirm condensation, underperformance, air quality, and comfort risks
Cumulative impact	Piecemeal retrofits are common; clarity is needed on impact of different options including achieving EPC band C.
Fabric vs ventilation	Insulation influences fabric & ventilation heat loss yet models currently only attribute savings to U-value changes.
Floor retrofit	80 % of homes have uninsulated floors; clarity on benefits may increase installation from 0.5% of ECO measures.
Airtightness retrofit	Infiltration undermines retrofits; balancing airtightness and indoor air quality is an unexploited ECO opportunity.
Neighbour risk	Clarity is needed on whether whole house or staged retrofits affect condensation risk for neighbours

1.2 Case study research questions

Over the course of the three-year project and following advice from DESNZ, the wider DEEP Steering Group, and Expert QA panel, additional questions have been proposed and the objectives have been refined to develop seven discreet research questions. These are listed below and will be referred to when discussing the findings:

1. *What combinations of retrofits are needed to bring solid walled homes up to an EPC band C? Do these represent value for money and what challenges do they face?*
2. *To what extent do unintended consequences reduce energy efficiency savings and increase moisture risks, when insulating solid walled homes?*
3. *Are methods to reduce the potential risk of unintended consequences when retrofitting solid walled homes effective and appropriate?*
4. *How significant is airtightness in domestic energy efficiency, and is improving airtightness a practical, low risk retrofit measure for inclusion in domestic energy efficiency policy?*
5. *How accurate can energy modelling of retrofits be, and how can EPCs be improved for use in retrofit performance prediction?*
6. *How can thermal modelling support risk management and retrofit energy modelling predictions?*
7. *How effective are low pressure Pulse tests and QUB tests as alternatives to the blower door test and the coheating test?*

Data collected from case study 56TR will contribute to the formation of a body of evidence from the DEEP project, that may begin to address these questions.

1.3 Case study house information

The case study, 56TR, shown in Figure 1-1 and Figure 1-2, was built around 1920 and is a 90 m^2 three-bedroom end-terrace property located in South Yorkshire. The three external walls (front, gable and rear) are made of solid nine-inch brick. The house has a large chimney stack to the gable wall, though the retrofitted gas fires have been blocked up. A positive input ventilation (PIV) system releases air from the loft into the stairwell.

56TR is a typical construction for the UK; around 1.3 million homes were built between 1919 and 1929 in England and Wales [1] and there are almost four million three-bedroom-terraced homes in the UK. There are likely to be around 200,000 homes very similar to 56TR, and around 1 million fairly similar two bedroom and three bedroom homes, though only a proportion of these are end- terraces [2].

The results obtained from 56TR provide a deep dive understanding of fabric and ventilation heat loss interactions. A much larger number of case studies would be needed to understand if similar experiences may be representative for equivalent homes in the UK.

Figure 1-1 Case study house

Figure 1-2 Case study house site location plan

Floor plans, elevations and sections of the case study can be seen in Figure 1-3 and Figure 1-4.

Figure 1-3 House floor plans

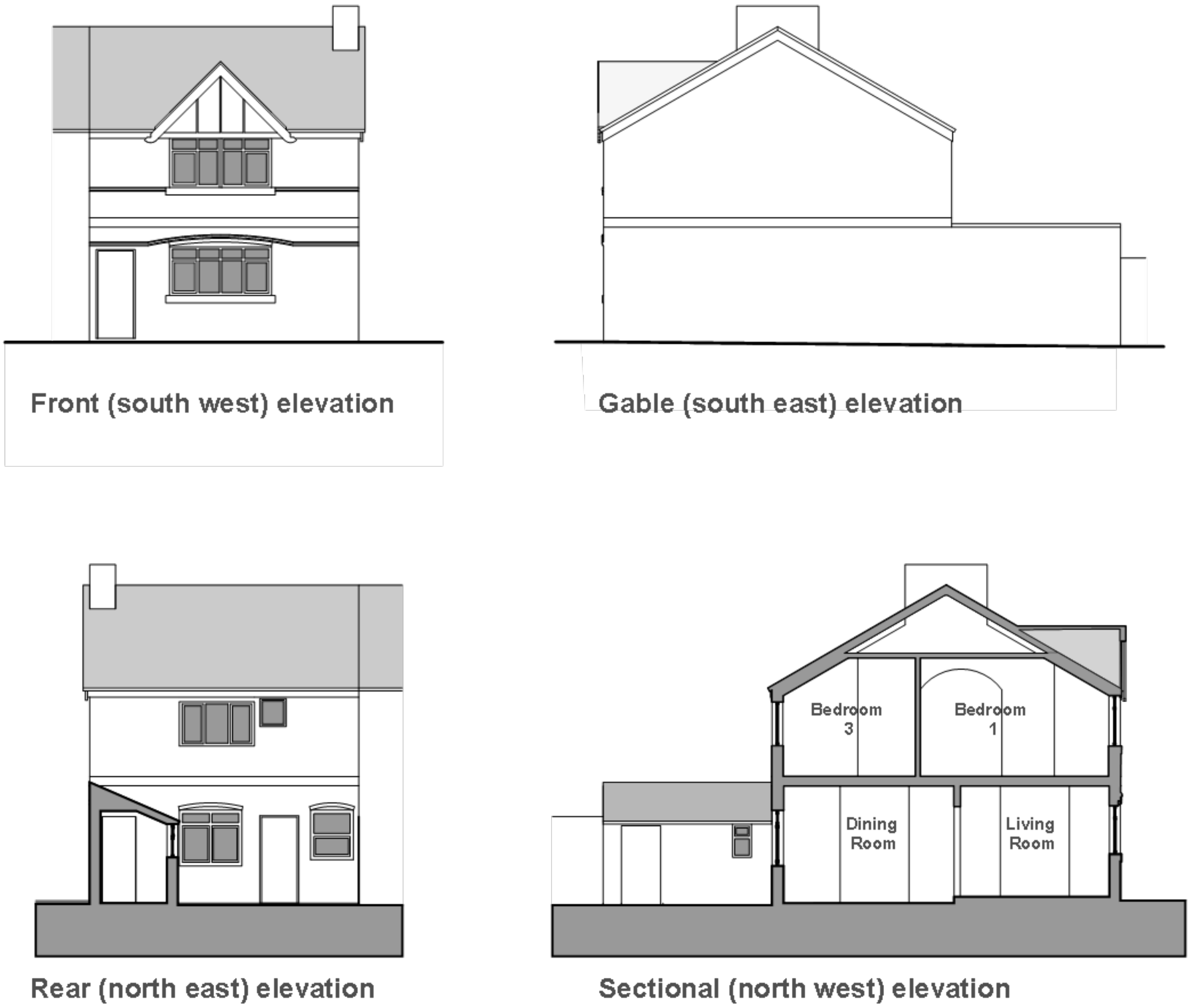


Figure 1-4 House elevations and sectional elevation

The dimensions of each element in the home are listed in Table 12. These dimensions were used to allocate heat losses as well as generate thermal models in RdSAP, BREDEM, and DSM.

Table 1-2 House dimensions

Detail	Measurement
Volume	*250 m^3*
Total floor area	*91 m²*
Total heat loss area	*211 m²*
Suspended timber ground floor	16 m²
Solid ground floor	31 m²
Rear external wall (north)	21 m²
Gable external wall, excluding chimney	33 m²
Chimney external wall	24 m²
Front external wall ground floor (south)	11 m²
Front external wall first floor (south)	9 m²
Windows	11 m²
Door	4 m²
Sloping roof	22 m²
Loft	28 m²
Party wall	42 m²

There were several notable construction features, that may be unrepresentative of similar properties of this type. For example, some TIWI (≈ 15 mm) was already installed in the dining room and bedroom 1.

In addition, the wall build-ups in parts of the house differed from the plastered finish expected, given the property's age. Drylining on dabs was found in the utility room, and the rear external wall part of the Ddning Room had been packed out and drylined to ensure that the TIWI ran flush across the wall above the utility room door.

Thermal imaging revealed a dry-lined plasterboard finish to the dining room gable walls either side of the chimney breast. The property had otherwise not undergone any other fabric retrofits. It was, however, generally in a poor state of repair with cracked plaster, signs of an historic leak around the chimney (which was now dry), and the suspended floor had 'dropped' slightly. Damaged 'boxing in' of pipes was observable where radiators and fires had been relocated or removed.

The single-storey, solid brick utility room lean-to, which was original, extended to encompass an outbuilding which was only accessible from the outside. Observations of the brickwork to the outbuilding part of the lean-to suggested that this part of the dwelling had been altered at some point.

High levels of mould growth were observed on the walls of the utility room, especially where the dot and dabs had been used to fix the plasterboard. The landlord confirmed that the washing machine and clothes drying had been located here which, consistent with the mould growth, is linked to moisture associated with drying clothes, with inadequate provision of ventilation and heating; i.e. was not linked to a leak or other structural damp issues. The home’s windows and doors were relatively new and were in good condition, so were excluded from the whole house retrofit.

1.4 Retrofit approach

The retrofit details and U-value targets for each element are listed in Table 1-3. The target retrofit U-values listed are calculated using the BRE calculator and are based on the observed materials and thickness of the existing fabric and knowledge of the insulation being installed. The thermal conductivity of the insulation was provided by the manufacturers and BS EN 12524:2000 was used and included calculation of repeating thermal bridges within each plane element calculation (e.g. floor joists). Non-repeating thermal bridges were modelled separately as described in Section 2.6.

Table 1-3 Construction and retrofit summary

Detail	Original construction	Retrofit[1]
Airtightness	8.17 $m^3/(h \cdot m^2)$ @ 50Pa	None.
Loft	Bedroom ceiling, cold roof, insulated with approximately 270 mm mineral wool	Mineral wool between and across joists 420 mm @ 0.044 W/(m·K) Target U-value 0.10 W/(m²·K)
Ground floor	Uninsulated suspended timber	Mineral wool between joists 200 mm @ 0.044 W/(m·K) Target U-value 0.20 W/(m²·K)
External wall type 1 (gable)	Uninsulated 9-inch solid brick	EWI mineral wool system (102 mm @ 0.033 W/(m·K) + 10mm ventilated cavity + 10mm façade) Target U-value 0.31 W/(m²·K)
External wall type 2 (front & rear)	Uninsulated 9-inch solid brick	IWI Woodfibre board 52 mm @ 0.043 W/(m·K) Target U-value 0.55 W/(m²·K)
External wall type 3 (gable)	9-inch solid brick with areas of 15mm XPS plasterboard IWI	EWI mineral wool system (102 mm @ 0.033 W/(m·K) + 10mm ventilated cavity + 10mm façade) Target U-value 0.27 W/(m²·K)
Windows & door	uPVC double glazed window & composite door	None
Whole house approach	a. Below damp-proof course uninsulated b. No Insulation to sloping ceilings	a. Below DPC XPS 75 mm@ 0.033 W/(m·K) Target U-value 0.36 W/(m²·K) b. Woodfibre to sloping ceiling 50 mm @ 0.038 W/(m·K) between rafters 40 mm @ 0.041 W/(m·K) on top of rafters Target U-value 0.46 W/(m²·K)

[1] Target U-values based on assumed construction details and may vary from Approved Document Part L maximums according to manufacturer recommendations or space limitations.

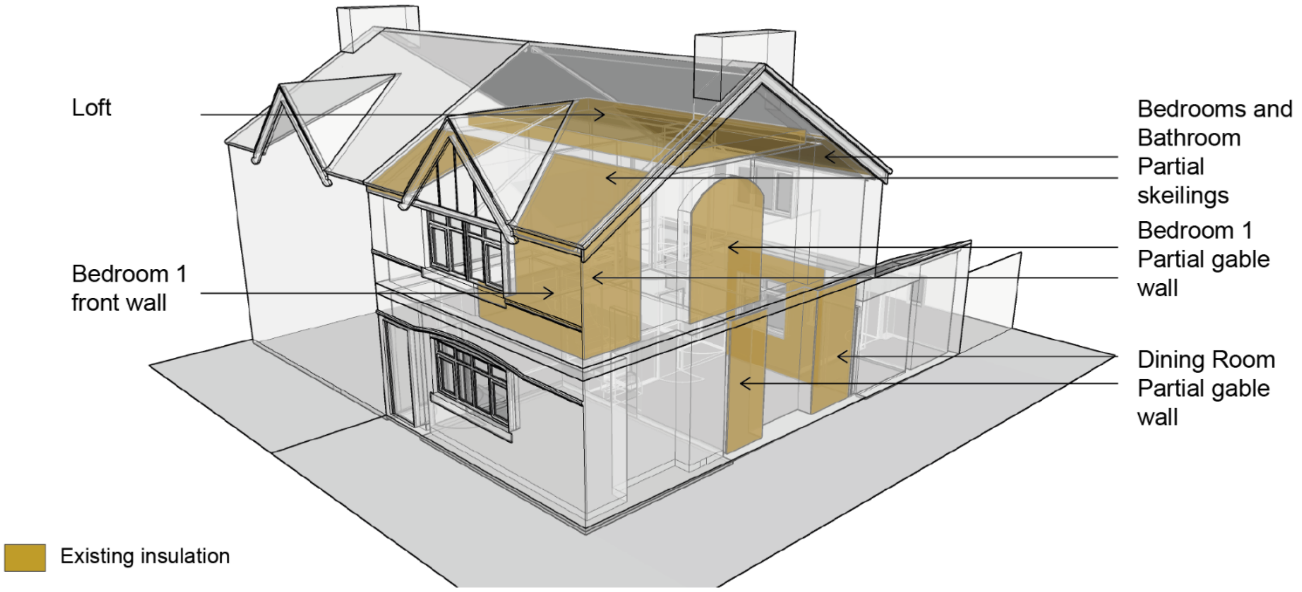
The sequence of the staged whole house retrofit approach is illustrated in Figure 1-6 through to Figure 1-9. Building Performance Evaluation (BPE) tests, whole house energy modelling and elemental thermal simulations were conducted at each stage of the retrofit to quantify performance changes associated with each separate intervention and the potential for condensation risk. The specific methodologies for these are described in DEEP Report 2.01.

The codes in Table 14 are shorthand to identify each retrofit stage. As the retrofits are cumulative, the codes are combined to explain which stage is being discussed, e.g. the final code for stage 4 is 56TR.R.F.W. The intention of stage 5 is to quantify impact on energy performance and moisture risks - activities that should take place as part of a whole house approach to retrofit (as discussed in PAS2035). Consequently, the case study home at this stage is referred to as 56TR.WH.

Table 1-4 Phased retrofit stages

	Retrofit stage	Code	Retrofit dates
1	Baseline	B	November 2020
2	Loft insulation	R	December 2020
3	Suspended timber ground floor insulation	F	January 2021
4	Internal and external wall hybrid insulation	W	February 2021
5	Whole house approach	WH	March 2021

2.03 DEEP 56TR



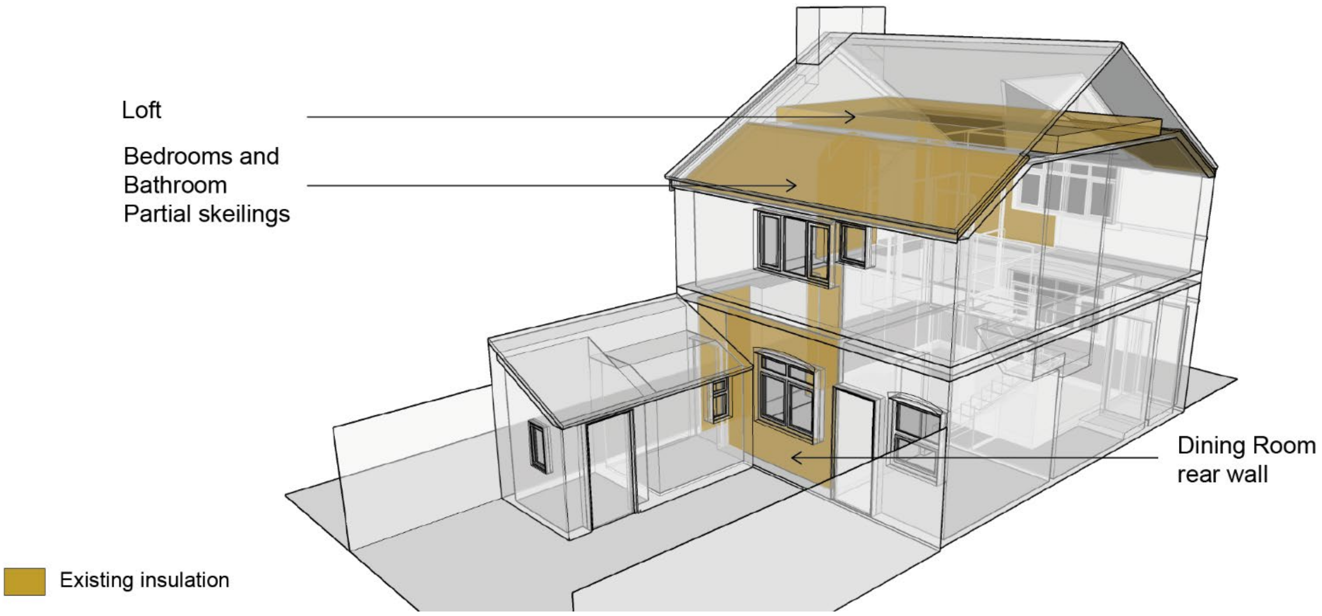
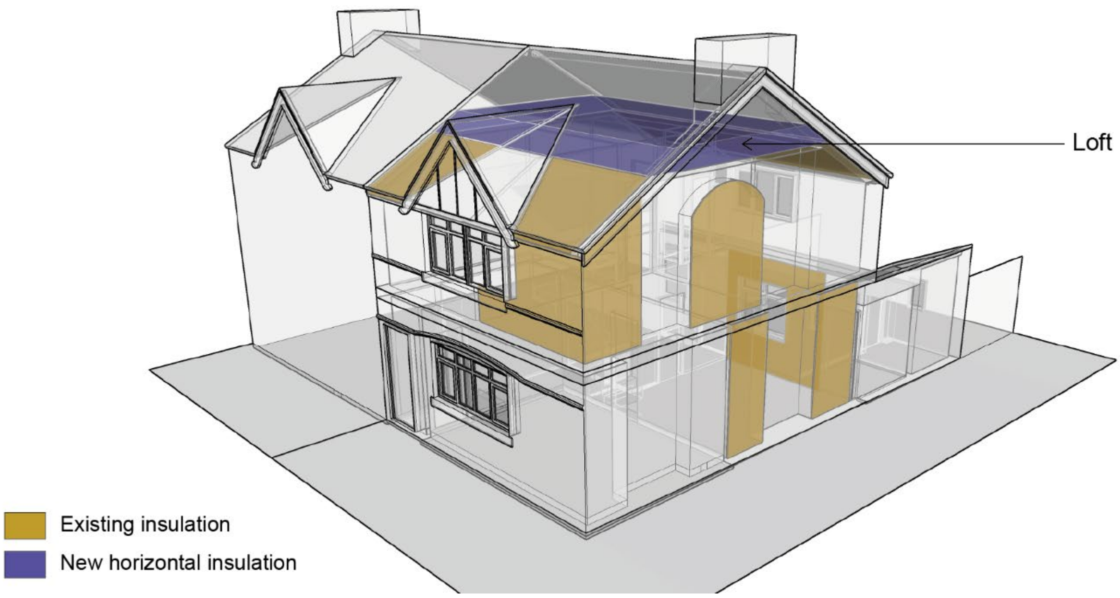


Figure 1-5 Stage 1: Insulation already in the property prior to the retrofits (56TR.B). Front & side elevations and rear elevation respectively.

2.03 DEEP 56TR



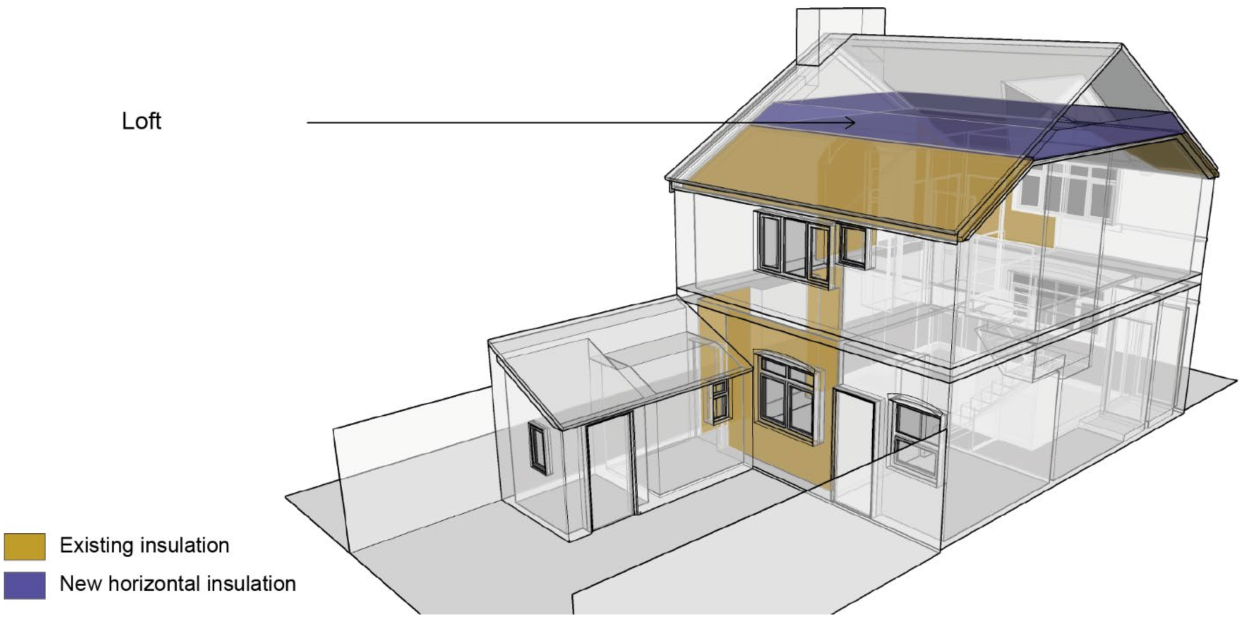
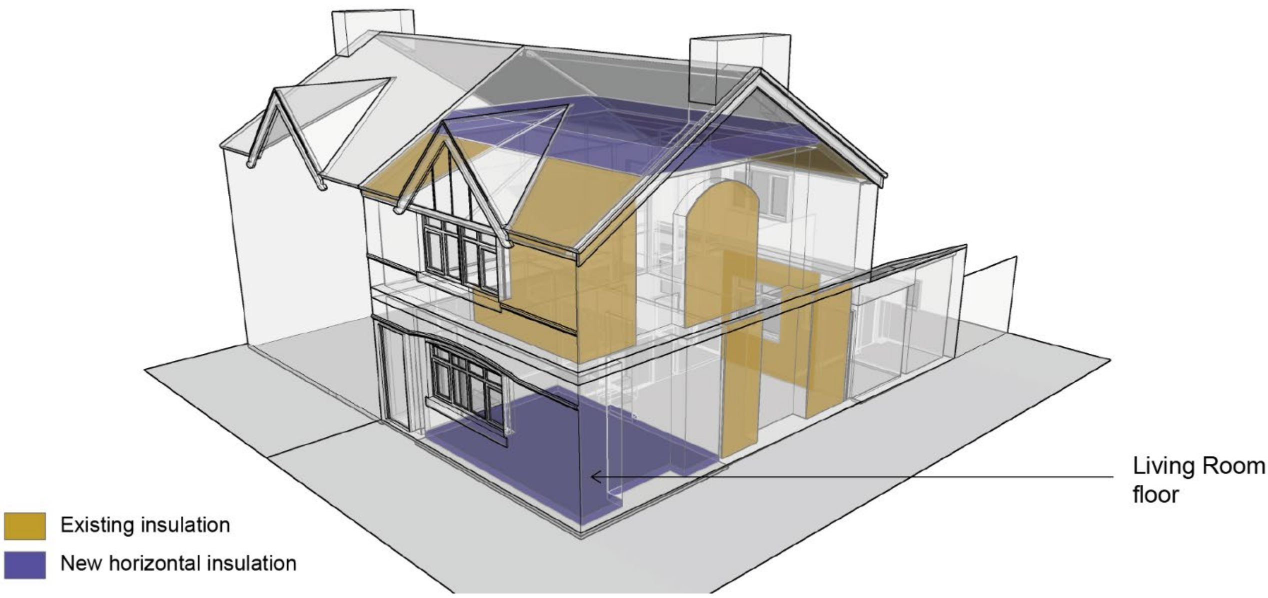


Figure 1-6 Stage 3: Roof retrofit to loft, where the existing insulation is removed and replaced (56TR.R). Front & side elevations and rear elevation respectively.

2.03 DEEP 56TR



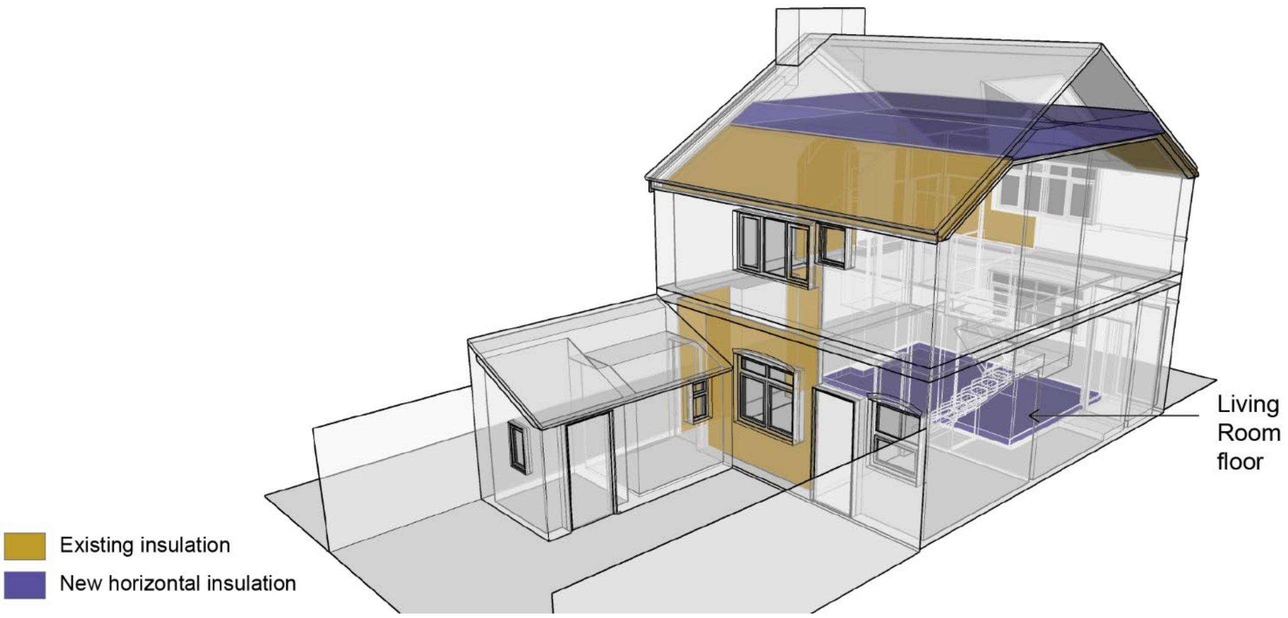
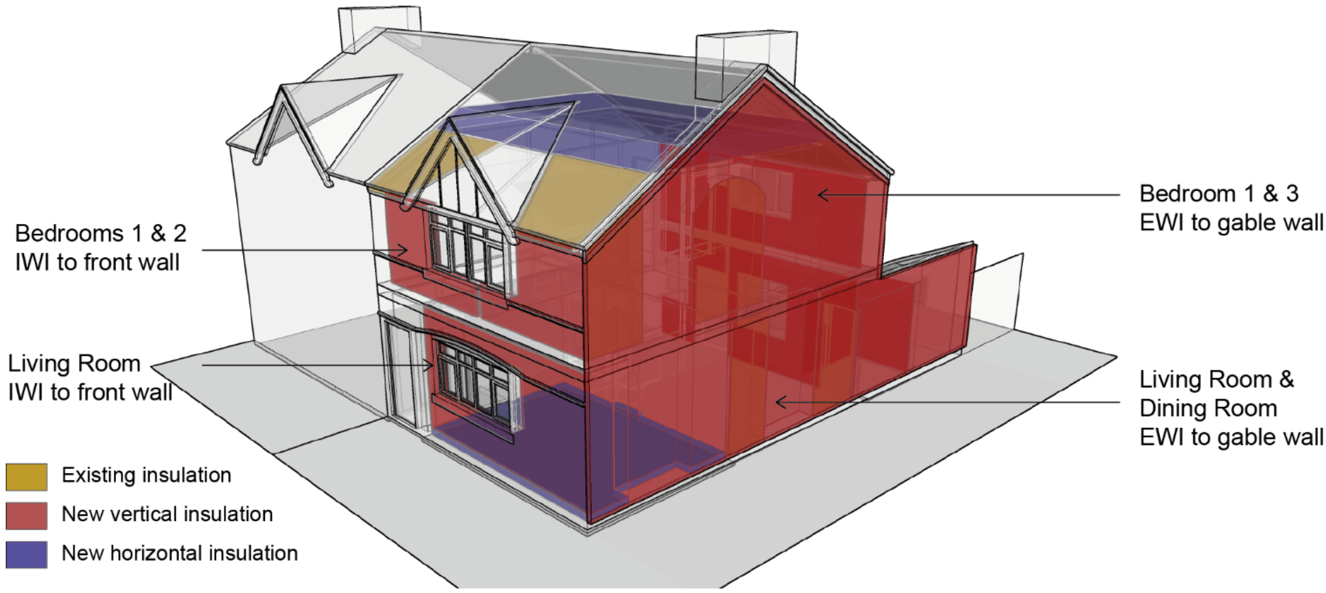


Figure 1-7 Stage 4: Floor retrofit to living room (56TR.R.F). Front & side elevations and rear elevation respectively.

2.03 DEEP 56TR



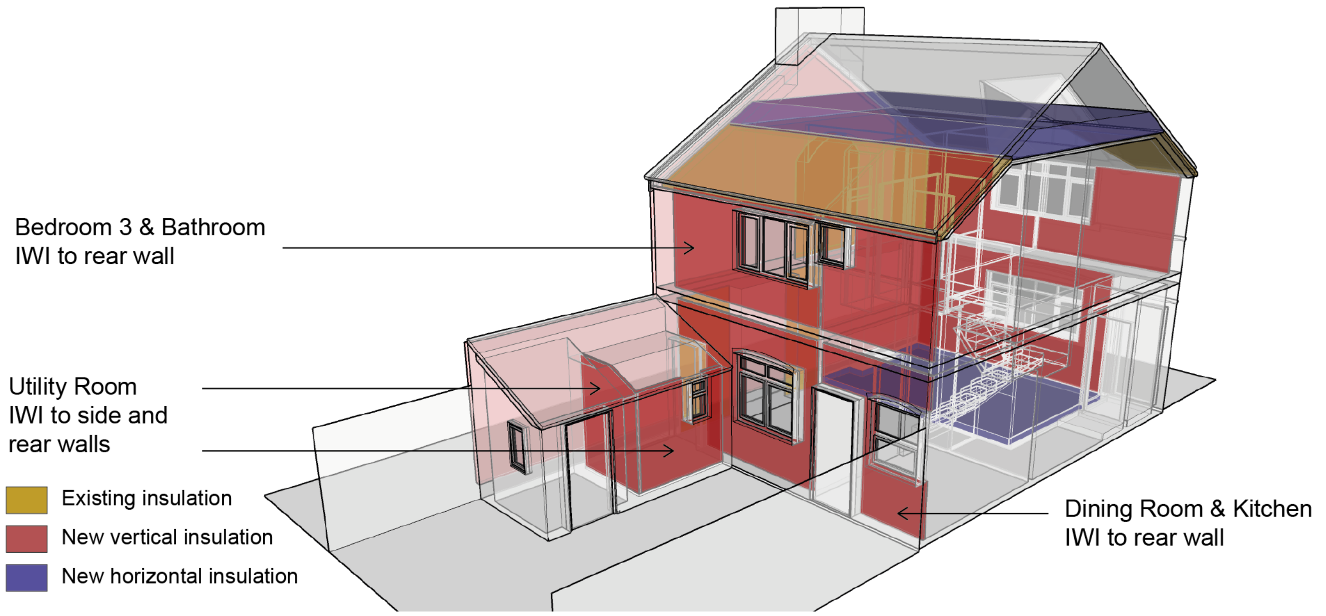
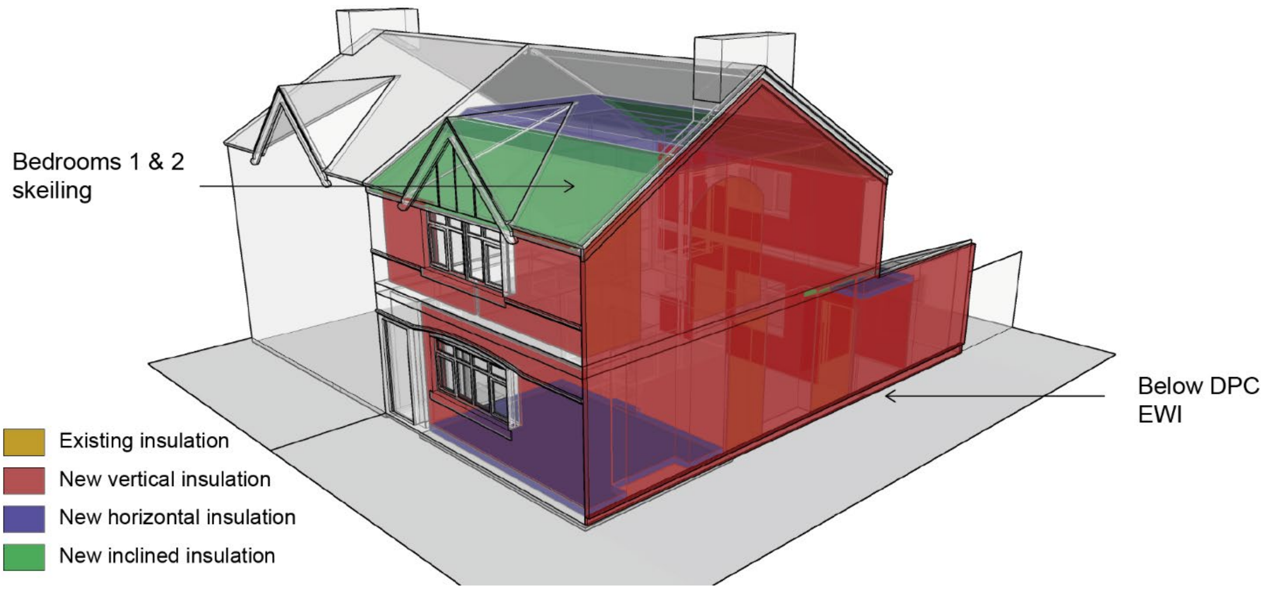


Figure 1-8 Stage 5: Hybrid approach to the wall retrofit. (56TR.R.F.W). Front & side elevations and rear elevation respectively.



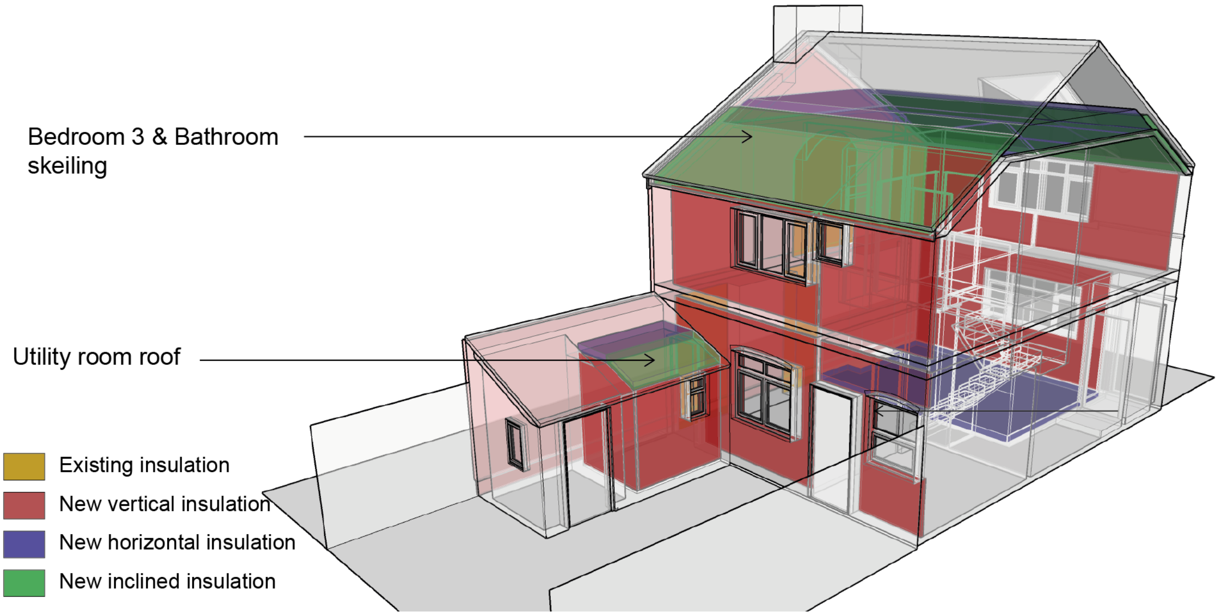


Figure 1-9 Stage 6: Whole house approach retrofit. (56TR.WH). Front & side elevations and rear elevation respectively.

Introduction summary

56TR provided an opportunity to install insulation in the loft and under the suspended part of a mixed ground floor construction, in an end-terrace 1920s solid walled case study home, collecting performance and moisture risk data.

It also provided the potential to investigate a hybrid approach to solid wall insulation where there is an interface between IWI and EWI.

Finally, it investigated the specific benefits of installing EWI below the DPC, and insulating skeilings, as part of a whole house versus piecemeal approach.

2 Fieldwork and modelling methods

BPE tests and modelling activities were undertaken on 56TR at each retrofit stage in accordance with the methodologies listed in DEEP Report 2.01. This section outlines the specific implementation of these methods at 56TR including any variations and additions.

2.1 Environmental data collection

Internal environmental data logging equipment is described in detail in the Methodologies Annex. Internal environmental data collected at 56TR included air temperature, Relative Humidity (RH) and CO_2 levels. External environmental data was collected via a mini weather station located on site, and included vertical solar irradiance, air temperature, and wind speed.

2.2 Measured survey

A detailed survey of the building was undertaken and from this a digital version of the house was developed using SketchUp. This model was used to calculate dimensions for each element and to draw up the plans shown in Figure 13. Plans, sections, and elevations were directly exported as DXFs to generate the geometry for use in Dynamic Simulation Modelling (DSM). The construction makeup of the existing building was also assessed where access could be gained to observe the material construction. Finally, core samples of the walls were also taken to perform lab analysis of the material properties and identify the construction layers, the method for which is described in DEEP Report 4.

2.3 Airtightness and thermography

Blower door tests were successfully undertaken at all baseline and retrofit stages. These results were used to identify airtightness changes related to the retrofits and to approximate heat loss attributable to ventilation (HTC_V). Qualitative thermography under depressurisation was undertaken and additional thermography, under normal conditions, of specific details was captured to identify changes between each retrofit stage. Pulse air test and CO_2 tracer gas tests were also deployed during the testing program to compare with the blower door tests results.

2.4 Heat flux measurement and U-values

26 Hukseflux HFP01 heat flux plates (HFPs) were installed on different elements in 56TR. These were installed to measure the improvements in U-values achieved by the fabric upgrades as well as quantify party wall heat loss experienced during the coheating test. The HFP locations are listed in Table 2-1 and visualised in Figure 2-1 and Figure 2-2. Thermography was undertaken to identify the most representative location for each fabric element and, where possible, multiple locations for each element were measured.

Heat flux data from individual HFPs along with internal and external temperature recordings were used to generate U-values for each element. Where more than one HFP was located on a single element, an average of the values was used to obtain a single U-value for the element. The U-values were used to calibrate energy and thermal models, to estimate the heat loss due to the fabric (HTC_f), and to compare this with the whole house HTC and disaggregation techniques. The in-situ U-values were based upon a limited set of measurements, so may not be representative of the performance of the element in practice.

When measuring U-values of walls, it's standard practice to either place HFPs on north-facing elements, or to install solar shielding [3]. Both these actions are intended to mitigate the effect of solar radiation on U-value measurements. However, given the varying levels of pre-existing insulation in 56TR, and given the different retrofit measures being installed, it was deemed necessary to place HFPs on the gable wall and front of the property, both of which received direct solar radiation. Due to safety constraints, it was not possible to install solar shielding. The U-value results from these elements may, therefore, be somewhat affected by solar radiation. However, the testing took place in winter, and it was always ensured that the stability criteria on ISO 9869 was met. Any impact of insolation is therefore likely to be minimal.

Due to the building geometry, a number of the HFPs had to be installed in non-idealised locations. In some areas where strong thermal bridging may be expected, such as near corners, heat flux density measurements were taken to provide context to the whole fabric heat loss and inform weighted average calculations.

While the BRE Calculator has the capacity to calculate the U-value of windows, in the case of 56TR, the necessary manufacturer details of the windows were not available. This included the glazing U-value, the frame U-value ,and internal construction to estimate the linear Ψ-value. The U-values for the windows had to be assumed and this therefore represents an area of uncertainty when considering accurate energy model inputs.

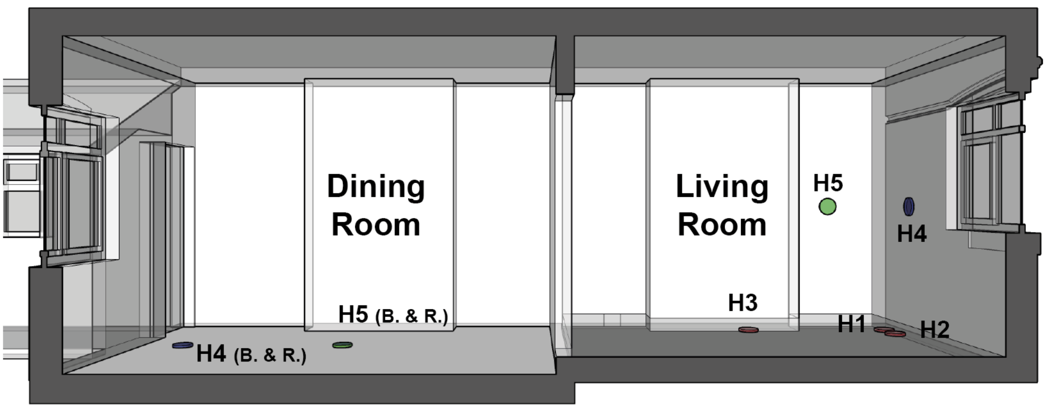
Table 2-1 HFP locations

HFP	Element	Room
H1, H2 H3	Suspended timber ground floor	Living room
H4[2], H5[3]	Solid ground floor	Dining room
AA13[4], AA14	Front external wall	Bedroom 1
AA1, AA2, AA3	Rear external wall	Bedroom 3
AA4, AA5, AA6	Gable wall	Bedroom 3
AA7, AA8	Gable wall	Bedroom 1
R1, R2, R3	Sloping ceiling (skeiling)	Bedroom 3
R4, R5	Ceiling	Bedroom 3
AA9	Chimney breast	Bedroom 3

[2] Installed for 56TR.B & 56TR.R, then moved to front external wall
[3] Installed for 56TR.B & 56TR.R, then moved to living room gable wall
[4] Installed for 56TR.B, 56TR.R & 56TR.F, then moved to window

2.03 DEEP 56TR

HFP	Element	Room
AA13	Window	Bedroom 1
AA10	Party wall	Bathroom
AA11	Party wall	Landing
AA15	Party wall	Bedroom 2
AA16	Party wall	Kitchen



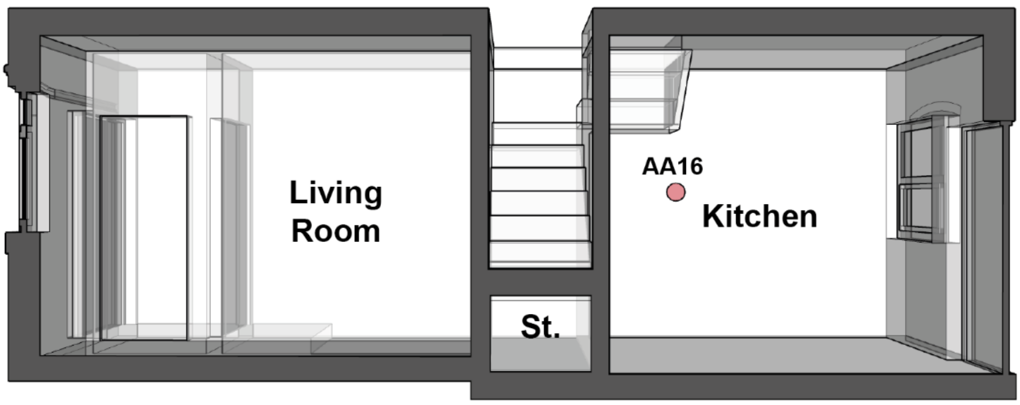


Figure 2-1 Ground floor HFP locations

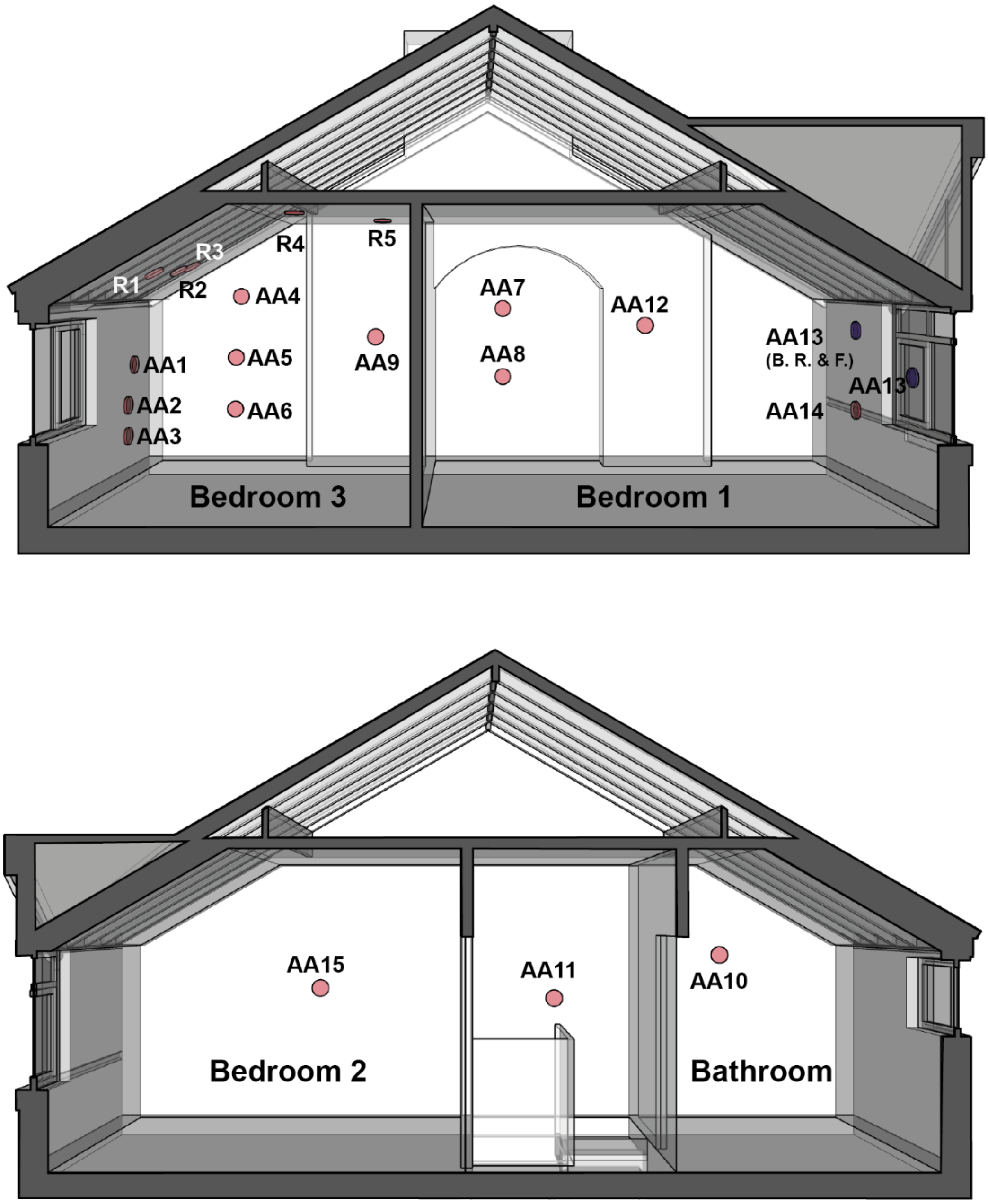


Figure 2-2 First floor HFP locations

2.5 Whole house heat transfer coefficient (HTC)

Coheating tests were successfully performed at each stage of the retrofit, as described in DEEP Report 2.01, to provide a measured HTC. In addition to coheating tests, QUB tests were attempted, and the results are presented for comparison, where available.

2.6 Surface temperatures and thermal bridges

There were several areas of interest in 56TR where there was risk of thermal bridging. In these areas, surface temperatures were measured to calculate the temperature factor (f_{Rsi}) and assess surface condensation risk. These are described in Section 3, and summarised here:

- Front wall to gable wall junction
- Gable wall to ceiling junction
- Intermediate floor / external wall junction
- Partition wall to external wall junction

2.7 Whole building energy modelling

The modelling methodologies undertaken are explained in detail in the Report 2.01 DEEP Methods. DEEP first used the steady- state energy model, BREDEM, which generates EPCs for existing homes via the RdSAP software. Using RdSAP means that EPC assessors interact with BREDEM using standard conventions and input defaults. DEEP compared how these restrictions affected the HTC that BREDEM predicts. These were also compared with the HTC predicted by Dynamic Simulation Modelling (DSM) (using DesignBuilder software version 7.0.0.088 [4]) at each retrofit stage. Table 2-2 describes the approach taken to understand how their predictions change as default inputs are overridden.

Table 2-2 Modelling calibrations stages

Calibration step	Infiltration	U-values	Bridging
1	Default[5]	Default[5]	Default[6]
2	Measured[7]	Default[5]	Default[6]
3	Measured[7]	Calculated[8]	Default[6]
4	Measured[7]	Measured[9]	Default[6]
5	Measured[7]	Measured[9]	Calculated[10]

Additionally, the models predict annual energy demand, annual heating cost, carbon dioxide emissions, SAP score, and EPC band. The modelled success of the retrofits can thus be evaluated using these metrics. Furthermore, when combined with the retrofit install costs, simple payback periods for each retrofit can be calculated.

[5] Provided by Appendix S RdSAP 2012 version 9.94
[6] Provided by Appendix K RdSAP 2012 version 9.94
[7] Derived from blower door test
[8] Derived from BRE Calculator
[9] Derived from heat flux plate measurements
[10] Calculated from TRISCO bridging simulations

By learning about the variability of the different models and how they compare to as-measured data, recommendations may be possible for improvements to both the models and the ways they are used. Improved understanding of modelling uncertainty may lead to better informed retrofit decision making at individual dwelling and national policy levels.

2.8 Elemental thermal modelling

In addition to the whole house energy models, elemental thermal modelling was undertaken to calculate non-repeating thermal bridging heat losses in the case study dwelling before and after retrofits. The modelling procedure is described in detail in Report 2.01 DEEP Methods. Modelling the Ψ-value (Psi-value) of junctions allows the thermal bridging heat loss (HTCb), to be calculated. This can be useful when evaluating the appropriateness of default values in RdSAP in the context of retrofit evaluation and, specifically, how it can affect the whole house HTC.

Thermal modelling also identifies surface condensation risks i.e. the minimum temperature factor (ƒRsi) for each of the junctions that may exist in the house pre- and post-retrofit. Where different retrofit strategies are considered, thermal modelling is able to compare the risks associated with piecemeal vs whole house retrofits.

In 56TR, thermal bridging calculations were performed for all 46 unique junctions under the four different retrofit scenarios and the pre-retrofit base case. Material properties were taken from default tabulated values and manufacturer data where available. Measured brick thermal properties were used to refine wall thermal conductivities in additional simulations, and a comparative analysis to default simulation results undertaken.

Case study method summary

A deep dive into the 56TR retrofit case study was undertaken involving coheating tests, blower door tests, and 26 heat flux density measurements on fabric elements, taken before and after each of the four retrofits performed.

Steady-state and dynamic energy models were also undertaken, to compare against these in-situ measurements. To investigate the appropriateness of using default data in energy models, a 5-step calibrated process was adopted.

Thermal models of 46 different junctions in the house under the different retrofitted scenarios were also undertaken to explore the impact of retrofits on the heat loss and condensation risks posed by thermal bridging. These models were refined using known construction material properties taken from wall core samples.

These methods collectively investigate the energy performance and condensation risk associated with different approaches to retrofit, as well as the usefulness of models in the prediction of these factors.

3 Results

This chapter first presents results on the in-situ field trials: airtightness tests, U-values, and the whole house heat loss as measured by the coheating and QUB tests. It then describes how modelled predictions compared with the measured data and how successful the five calibration steps were. The outputs are discussed in terms of their EPCs, space heating, CO_2 emissions, fuel bills, and paybacks. Finally, the potential surface condensation risks posed in the house at each retrofit stage are discussed.

3.1 Airtightness improvements

The base case status of the house did not have excessively high or low levels of air leakage: its infiltration rate was found to be 8 $m^3/(h \cdot m^2)$ @ 50Pa. For context, the average UK air permeability rate is estimated to be approximately 11.5 $m^3/(h \cdot m^2)$ @ 50Pa [5] and the limiting value permitted under Building Regulations for new builds is now 8 $m^3/(h \cdot m^2)$ @ 50Pa [6]. The house, therefore, would comply with the limiting value contained within the 2022 Building Regulations for new build dwellings.

It is important to note that the air permeability rate is not the same as ventilation for fresh air, for which there was purpose provided ventilation via trickle vents on windows, a loft-mounted Positive Input Ventilation (PIV) system providing trickle input above the stairs, and electrical intermittent extraction fans located in the bathroom and kitchen. These were all retained throughout the retrofit. There was an opening for a fan in the single-story extension being used as a drying room, but no fan had been fitted prior to retrofit. This was rectified in the final stage of the retrofit. Since the house was already deemed to be relatively airtight, by existing UK standards, no dedicated airtightness retrofit was planned. However, the change in airtightness achieved during the retrofit stages was still measured and recorded and is shown in Figure 3-1.

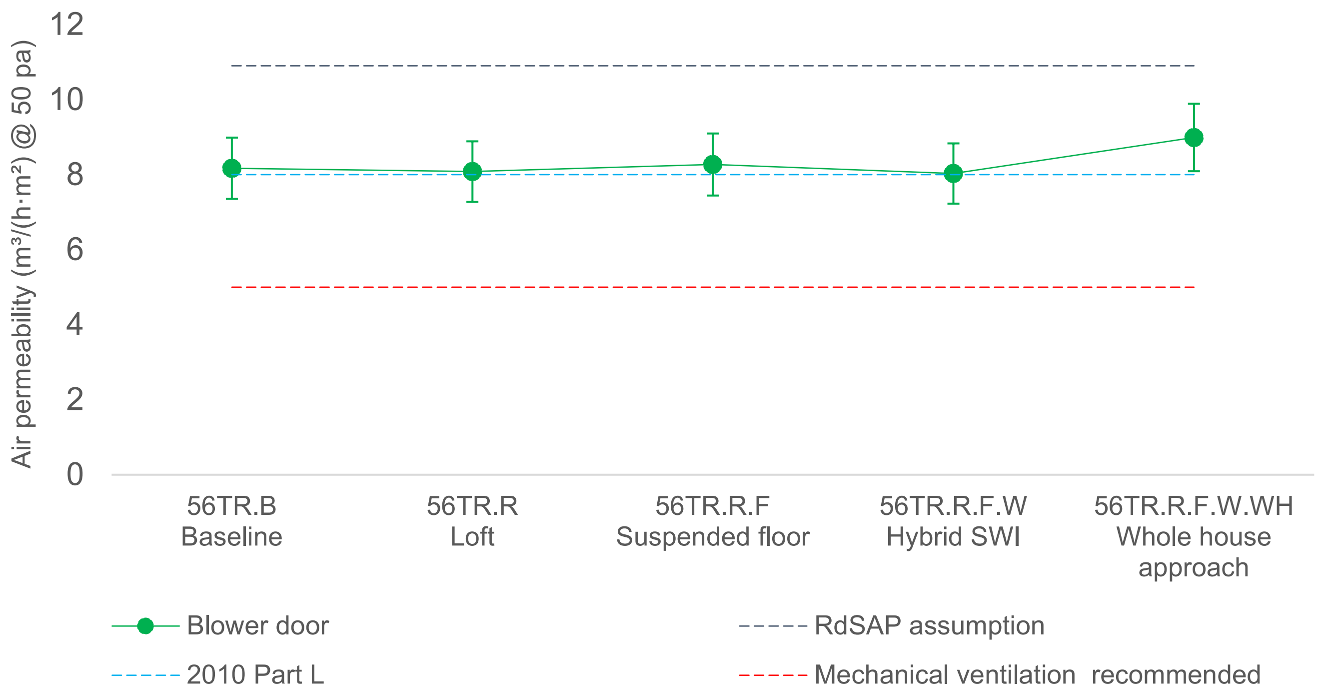


Figure 3-1 Airtightness measurements made at each retrofit stage

Figure 3-2 to Figure 3-6 show major air leakage routes identified pre- and post-retrofit in the airtightness test under dwelling depressurisation, consisting mainly of:

- the perimeter of the suspended timber ground floor and intermediate floor void
- the seals of external doors and closed trickle vents on windows
- behind dot and dab wall and sloping ceiling linings
- around the loft hatch
- some unsealed service penetrations

The suspended timber ground floor was unsealed and so the infiltration here illustrates air exchange with the ground floor void. Air movement behind the dot and dab boards suggests air movement is taking place through the solid brick wall, and that the dot and dab boards had also not been fully sealed to the wall, by applying a continuous ribbon of plasterboard adhesive. Consequently, this allowed air to link to other areas within the dwelling.

Infiltration via the intermediate floor void, which was observed to be close to external temperatures under depressurisation, is suggestive of air exchange between the floor void and mini cavities in the external walls or with external services routes that enter the intermediate floor.

Air movement behind the sloping ceiling, coupled with multiple cold spots, suggests that the void is only partially insulated and external air is moving around the insulation and directly onto the sloping ceiling where this is exposed.

Figure 3-2 Infiltration at suspended floor perimeter during depressurisation post-retrofit

Figure 3-3 Infiltration at intermediate floor perimeter during depressurisation, pre-retrofit, also showing imperfectly installed sloping roof insulation, and existing thin internal wall insulation

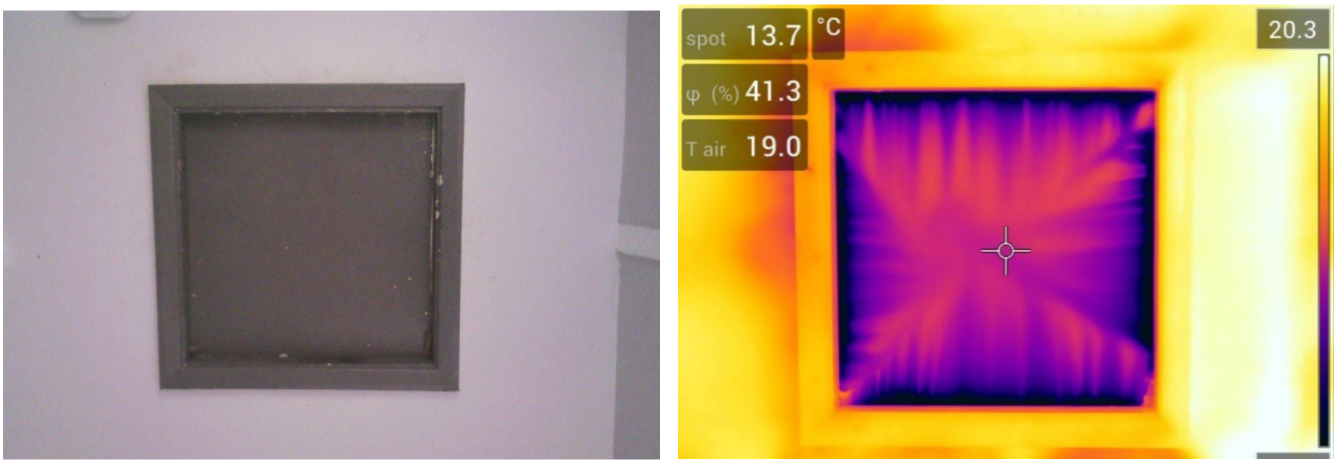


Figure 3-4 Infiltration at loft hatch edges during depressurisation pre-retrofit

No material change was made to the airtightness in the dwelling as a result of the retrofits. This was reflected in the blower door results for most stages. However, during the final retrofit stage (in which the retrofits were to ensure the whole house approach was followed), the absolute value of infiltration was seen to increase slightly. This was likely due to new plaster on the sloping ceilings shrinking and cracking where it joined the flat ceiling, enabling air to move behind the dot and dab plasterboards, as shown in Figure 3-5 and Figure 3-6.

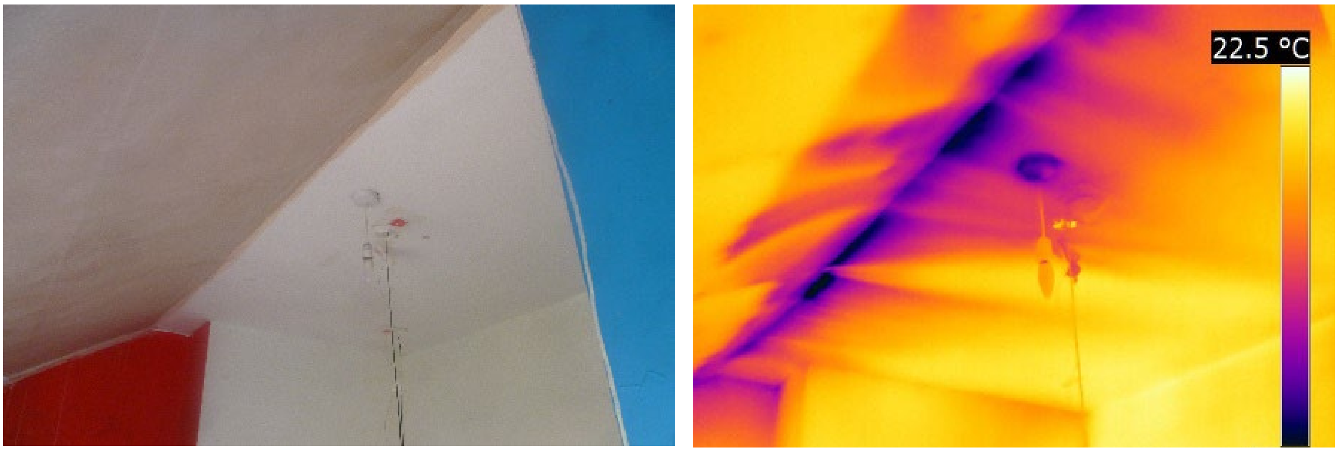


Figure 3-5 Infiltration between sloping and flat ceiling during depressurisation post-retrofit

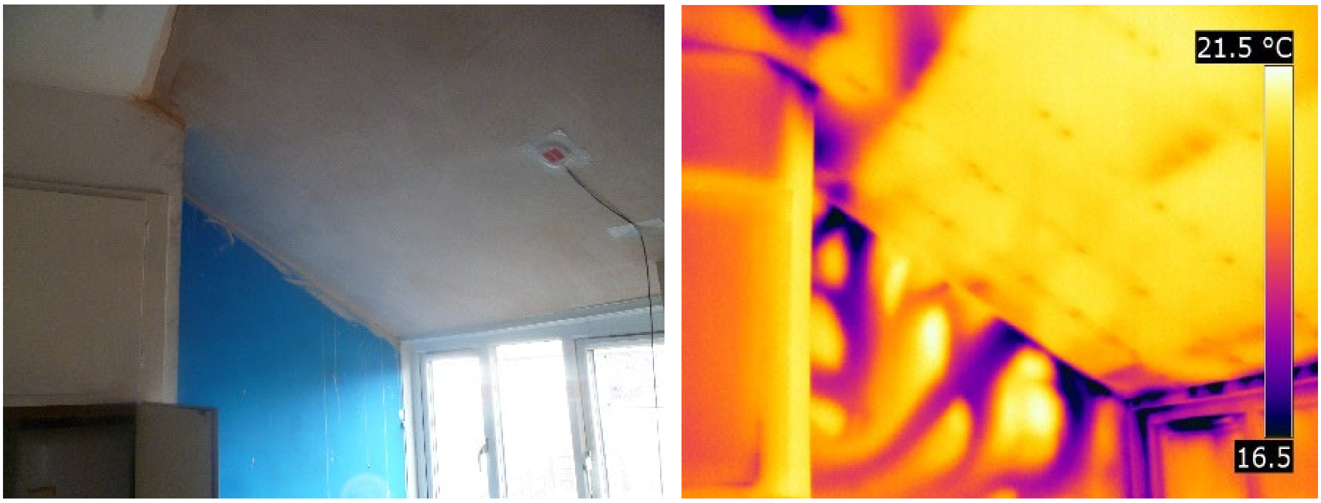


Figure 3-6 Air movement behind dot and dab plasterboard on partition wall during depressurisation post-retrofit

No change was made to the doors and windows throughout the property as they were in an adequate state on initial testing. The airtight performance of the window casements and seals was acceptable, but the seals around both external doors allowed significant air movement, as shown in Figure 3-7. The other notable infiltration point was through and around the trickle vents, many of which closed poorly and were not sealed to the window frames, as shown in Figure 3-8.

Figure 3-7 Air movement around the front door

Figure 3-8 Air movement at windows, directly at the closed trickle vent and indirectly around the frame into the void behind the jamb lining

3.1.1 Co-pressurisation tests

An additional test, known as a co-pressurisation test, was undertaken after the retrofits had taken place. The co-pressurisation test can identify how much of the infiltration measured by the blower door test was potentially air exchange with the neighbouring property rather than to the outside. Inter-dwelling air exchange under ‘normal’ (non-pressure-induced) conditions may not be substantial and, since both homes will normally be heated spaces, it may not be a heat loss mechanism under lived-in conditions. Thus, it is important to realise that using the blower door data to approximate infiltration may result in an overestimation of infiltration heat losses (HTC_V).

When holding both properties at 50Pa, the drivers for inter-dwelling air exchanges are eliminated and the air permeability dropped from 8.99 $m^3/(h·m^2)$ @ 50Pa when fully retrofitted, to 7.52 $m^3/(h·m^2)$ @ 50Pa under pressurisation of both houses. This is a 16 % reduction in the non-co-pressurised figure and suggests that at these test pressures, this proportion of infiltration is inter-dwelling air exchange, involving conditioned air rather than external air. This is a phenomenon that is present for all blower door tests undertaken in homes with attached neighbours, tested in the DEEP project. This result has implications for compliance testing and energy performance as well as payback calculations for retrofits. However, more research is needed to understand the relationship between building form, building age, party wall types, and number of adjacent dwellings to understand this relationship and the potential implications.

3.1.2 Pulse tests and CO_2 decay tests

Pulse tests offer an alternative means of assessing the infiltration of homes without inducing excessive pressures. Two Pulse tests were undertaken at 56TR, at the baseline and final whole house stage. Both predicted higher results (by 26 % and 51 % respectively) when compared to the blower door test, even when the uncertainty of each test is taken into consideration.

A result from the Pulse test is given for a pressure difference of 4Pa, and a standard correction is recommended to convert this figure to an equivalent 50Pa pressure differential [7]. While this does not accurately correlate with the blower door test result and appears to be over estimating air leakage, it too concurs that there may have been a slight increase in airtightness following the retrofit.

Unfortunately, it was not possible to obtain reliable CO_2 tracer gas decay data, meaning it was not possible to use the data collected to validate the approximated air changes identified by the blower door or Pulse test in this test dwelling.

Airtightness improvement summary

The case study home already had reasonable levels of airtightness, comparable with the backstop new build Building Regulations standard of 8 $m^3/(h·m^2)$ @ 50Pa. Importantly, airtightness was not materially affected by the retrofit.

Slight increases measured post whole house approach retrofits can be explained by accelerated drying and settlement, which would be reduced by normal decoration, but were still within the uncertainty of the test.

3.2 U-value improvements

Three methods were adopted in deriving U-values:

1. **RdSAP default U-values:** using age-related band default assumptions provided in SAP Appendix S, the most common approach used in EPCs for existing homes.
2. **Calculated U-values:** used where construction details are known and a calculation is undertaken in separate approved software (e.g. the BRE U-value calculator).
3. **Measured U-values:** used where in-situ heat flux density measurements were undertaken using an approved methodology. This approach is the most specialist and costly to undertake and so is the least likely to be undertaken in retrofit projects.

All three methods were used in DEEP for comparison and this section reports on the difference between them. The report considers implications of the method selected on accuracy of energy and heat loss predictions, the contribution of fabric elements to the HTC, and the predicted benefit achieved by retrofits.

A summary of the before and after U-values for each of the fabric elements is presented in Figure 3-9 and Figure 3-10. Reductions were achieved where insulation was added to the suspended timber floor, ceiling, and sloping ceiling, though the solid floor was not insulated.

The uPVC window and door U-values are not presented as no changes to these elements were made and, although centre-pane window U-values were measured, it was not possible to obtain manufacturers details around the frame thermal performance. Default U-values based on RdSAP age bands were therefore assumed for these elements.

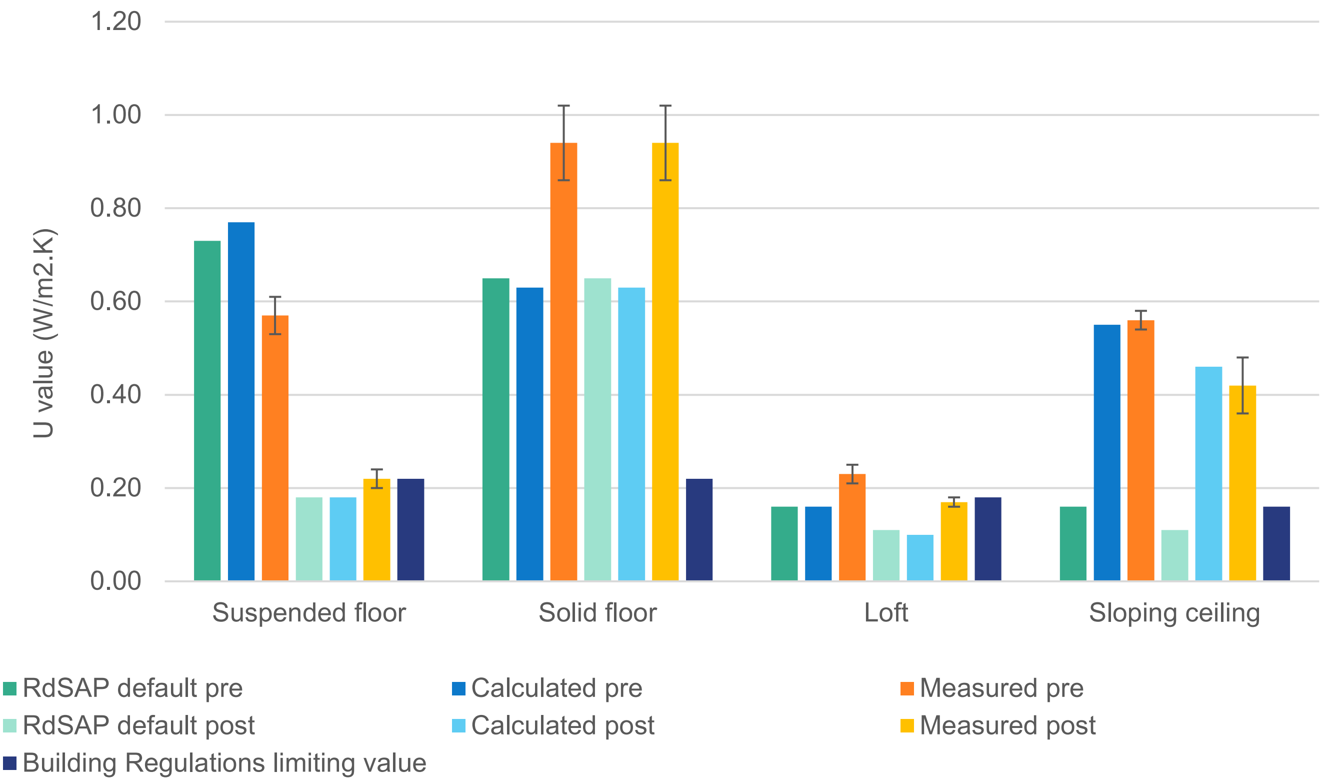


Figure 3-9 Pre- and post-retrofit fabric U-values (W/(m²·K)) of floors and ceilings

As can be seen, the limiting Building Regulations U-values were not achieved when insulation was added to the sloping ceiling. The reason for this was that there needs to be an air gap maintained between the roof and the back of the insulation and so the thickness of insulation that could be installed was not enough to achieve the limiting value. This is likely to be a common scenario when retrofitting all skeilings in the UK.

The pre-retrofit measured U-values for the suspended ground floor were slightly lower than the calculated and default predictions, while conversely, they were higher for the solid ground floor. This means that the suspended ground floor retrofit is predicted to have a bigger heat loss reduction than may be achieved in practice and that the heat loss attributable to the solid ground floor may be greater than it is predicted to be.

The pre-retrofit ceiling U-value was slightly higher than the calculated and RdSAP U-value defaults predicted, meaning there may be some benefit in reinsulating the loft in practice, but models which rely on default U-values would not predict that any benefit would be achieved. This has implications for the predictions of the remaining potential loft retrofits that there are in the UK, i.e. lofts classified as insulated may in reality benefit from top-ups or reinsulation, but EPCs are not able to capture this benefit.

The default, calculated, and measured pre- and post-retrofit U-values for the external walls are presented in Figure 3-10. The variation in uncertainty shown may in part relate to the effect of solar irradiance heating up the external walls and affecting the measurements more in the post-retrofit period than in the pre-retrofit (the house was not orientated due north so some solar affected north facing walls).

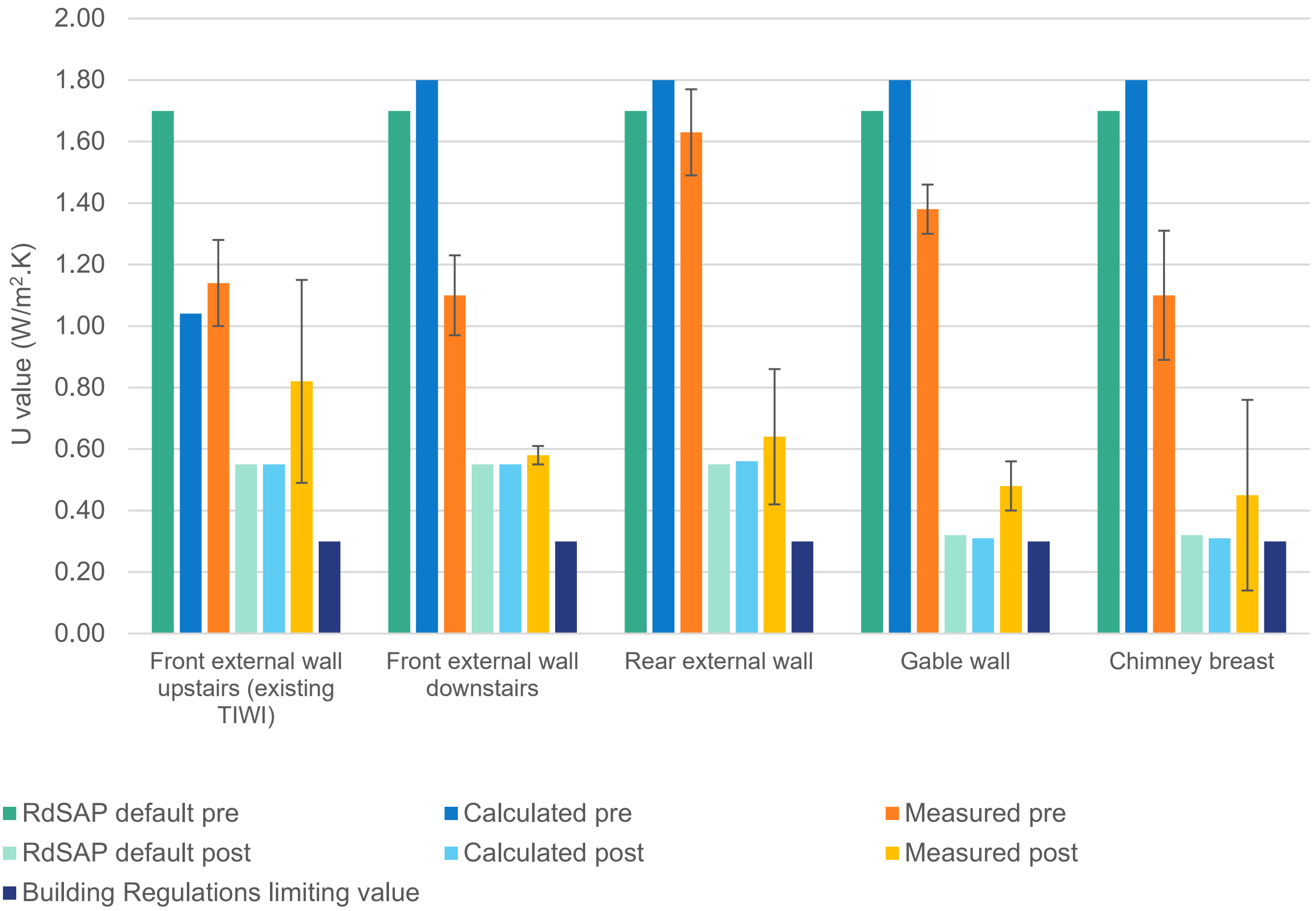


Figure 3-10 Pre- and post-retrofit external wall U-values (W/(m²·K))

The gable and front external wall already had dry lining installed pre-retrofit which consisted of 12 mm of polystyrene on a 9 mm plasterboard. This was fixed in position using dot and dab adhesive. Where this Thin Internal Wall Insulation (TIWI) was installed, the measured U-value was expected to be lower, since RdSAP does notconsider any insulation below 50 mm in thickness. However, external walls without TIWI were also measured to have much better U-values than the RdSAP default for homes of this age.

The uninsulated solid-wall U-values measured in 56TR were lower than found in other studies. For example, work by the BRE found an average value of 1.77 W/(m^2·K) [8]. However, this previous work also noted the large variability in measured U-values, with values ranging between 1.1 W/(m^2·K) and 2.2 W/(m^2·K) being measured in different solid-walled homes.

One reason put forward to explain this variability is that solid brick external walls can have an inhomogeneous finger air cavity. These small gaps between inner and outer stretcher courses vary with brick bond types and can change the thermal and hygroscopic properties of the wall. Another potential reason is varying levels of moisture with the brickwork, potentially caused by the different exposures of elements to weather [8].

Whatever the cause, considerable variability was present in 56TR both between wall elements, and also across the same wall element. For example, six HFPs were placed on the gable wall, and measured U-values from these plates varied between 1.4 and 2.0 W/(m^2·K) (average value of 1.63 W/(m^2·K)). This variability illustrates the difficulty in obtaining whole element U-values from spot heat flux density measurements even when multiple HFPs are used. Heterogeneity in fabric is always an area of uncertainty when deriving U-values using HFPs [9, 10].

The percentage improvements in U-values achieved for all elements measured are listed in Table 1-3. As can be seen, the improvement in the U-values measured was variable across elements, as was the uncertainty on individual values. In general, the uncertainty associated with HFPs not on south facing elements was found to be smaller. This confirms the challenge in obtaining reliable U-values based on HFPs for south facing walls due to excessive insolation and suggests that some form of temporary solar shielding may be needed if U-values of south facing walls need measuring.

In RdSAP, chimneys are considered to have equal heat losses as external walls. In practice, as can be seen in Table 32, the chimney void can act as a semi exposed space and therefore reduce heat losses through adjacent parts of the wall. This was observed to be taking place in 56TR, which had an uninsulated gable wall external U-value of (1.38 ± 0.08) W/(m^2·K), while the uninsulated chimney breast U-value was (1.10 ± 0.21) W/(m^2·K). This means the anticipated savings from EWI retrofits may be smaller than predicted in dwellings that have chimneys located on the external walls. However, it should be noted that unsealed chimneys could also act as a thermal bypass, potentially causing greater heat loss than neighbouring walls.

This may be an important phenomenon in those homes where chimneys represent a large proportion of the external wall area. In 56TR, the chimney is under 6 % of the total heat loss area. More research is needed to understand heat losses through different sizes and types of chimneys (ventilated versus sealed) and how this might impact savings achieved by SWI, national energy efficiency policy, and the potential to incorporate chimney heat losses separately from the rest of the wall in EPCs.

It is worth mentioning that the IWI retrofit was not designed to achieve the building regulations target of 0.3 W/($m^2 \cdot K$) since the manufacturer's calculations recommended a less stringent 0.55 W/($m^2 \cdot K$) target to minimise the risk of interstitial condensation as per best practice [11].

Table 3-1 RdSAP Default, calculated, and measured U-values (W/(m2·K))

	Pre-retrofit U-value			Post-retrofit U-value and % improvement		
	RdSAP default	Calculated	Measured	RdSAP default	Calculated	Measured
Suspended ground floor	0.73	0.77	0.57 ± 0.04	0.18 (75 %)	0.18 (77 %)	0.22 ± 0.02 (61 ± 4) %
Solid ground floor	0.65	0.63	0.94 ± 0.08	-	-	-
Front external wall upstairs (with TIWI)	1.70	1.04	1.14 ± 0.14	0.55 (68 %)	0.55 (47 %)	0.82 ± 0.33 (28 ± 36) %
Front external wall downstairs (without TIWI)	1.70	1.80	1.10 ± 0.13	0.55 (68 %)	0.55 (69 %)	0.58 ± 0.03 (47 ± 13) %
North external wall	1.70	1.80	1.63 ± 0.14	0.55 (68 %)	0.56 (69 %)	0.64 ± 0.22 (61 ± 26) %
Gable wall (without TIWI)[11]	1.70	1.80	-	0.32 (81 %)	0.31 (83 %)	-
Gable wall (with TIWI)	1.70	1.04	1.38 ± 0.08	0.32 (81 %)	0.27 (74 %)	0.48 ± 0.08 (65 ± 11) %
Ceiling	0.16	0.16	0.23 ± 0.02	0.11 (31 %)	0.10 (38 %)	0.17 ± 0.01 (26 ± 2) %
Chimney breast	1.70	1.80	1.10 ± 0.21	0.32 (81 %)	0.31 (82 %)	0.45 ± 0.31 (59 ± 37) %
Sloping ceiling (skeiling)	0.16	0.55	0.56 ± 0.02	0.11 (31 %)	0.46 (16 %)	0.42 ± 0.06 (25 ± 6) %

The results in Table 3-2 also suggest that there can be a considerable gap between what EPCs assume, compared to what is experienced in-situ. These gaps may be somewhat expected, since the RdSAP baseline solid external wall U-value does not account for the TIWI. Thus, much of the gap could actually be due to the use of defaults. These are therefore not only 'performance gaps', but 'prediction gaps'. We define these two gaps as follows and calculate their values in Table 3-2.

RdSAP defaults prediction gap = difference between the predicted reduction in U-value from RdSAP compared to the measured reduction in U-value.

Performance gap = difference between the predicted reduction in U-value from a calculation method (e.g. the BRE U-value calculator) compared to the measured reduction in U-value.

[11] No HFP recordings were obtained for the gable wall without TIWI

Table 3-2 Summary of U-value reductions and gaps in performance. Numbers in red show a significant gap.

Element	RdSAP default predicted reduction (W/(m²·K))	Calculated predicted reduction (W/(m²·K))	Measured reduction (W/(m²·K))	RdSAP defaults prediction gap (W/(m²·K))	'as-built' performance gap (W/(m²·K))
Suspended floor insulation	0.55	0.59	0.36 ± 0.05	0.19 ± 0.05	0.23 ± 0.05
IWI front external wall upstairs (with TIWI)	1.15	0.49	0.32 ± 0.36	0.83 ± 0.36	0.17 ± 0.36
IWI front external wall downstairs (without TIWI)	1.15	1.25	0.52 ± 0.13	0.63 ± 0.13	0.73 ± 0.13
IWI north external wall	1.15	1.24	0.99 ± 0.26	0.16 ± 0.26	0.25 ± 0.26
EWI gable wall (without TIWI)[12]	1.38	1.49	-	-	-
EWI gable wall (with TIWI)	1.38	0.77	0.90 ± 0.11	0.48 ± 0.11	-0.13 ± 0.11
Ceiling	0.05	0.06	0.07 ± 0.02	-0.02 ± 0.02	-0.01 ± 0.02
Chimney breast	1.38	1.49	0.65 ± 0.38	0.73 ± 0.38	0.84 ± 0.38
Sloping ceiling (skeiling)	0.05	0.09	0.14 ± 0.06	-0.09 ± 0.06	-0.05 ± 0.06

Table 3-2 highlights the existence of some particularly large gaps. For example, RdSAP predicted a reduction of 1.15 W/(m²·K) for front external wall. The difference between this prediction and the measured reduction was (0.83 ± 0.36) W/(m²·K). As this element has a large area, the existence of this gap is likely to have considerable impact on the overall heat loss of the home.

Note also that for this element, no statistically significant change could be detected in the measured reduction. However, the uncertainty on the measured reduction is still sufficient to rule out a change as high as the 1.15 W/(m²·K) predicted by RdSAP. The as-built performance for this element, calculated with the BRE U-value calculator, did not overestimate the U-value reduction on this element by a significant margin.

It is important to note that the numbers in Table 3-2 relate only to prediction *reductions*. The absolute measured U-values can still be incorrect (as is the case for the ceiling U-values shown in Table 3-2). Thus, a smaller value for the gap in Table 3-2 indicates a better prediction of energy *savings* but does not necessarily suggest an accurate prediction of the overall heat loss of a property.

The sloping ceiling U-values are also noteworthy in this case study. RdSAP assumes these to be insulated to a high level with a U-value of 0.16 W/(m²·K) - much lower than the 0.55 W/(m²·K) that was measured. There was limited room to install insulation without lowering the ceiling, and there is a requirement to leave a 50 mm ventilation space between the insulation and the rafters.

[12] No HFP recordings we obtained for the gable wall without TIWI

Nonetheless, insulation was installed and a measured U-value of 0.46 W/(m²·K) was achieved. While this value is considerably higher than the 0.11 W/(m²·K) that RdSAP assumes post-retrofit, the addition of insulation where there previously was little caused a greater reduction in U-value than predicted by RdSAP.

The implication of this is that an assessment based on models may not recommend that these areas need to be retrofitted, though the measurements in this case study suggest they can provide substantial benefits. This could be important for national energy efficiency policy, since sloping ceilings can constitute a relatively large proportion of a home’s overall heat loss area. In 56TR, the sloping ceiling was almost 10 % of the total dwelling heat loss area. Therefore, this finding could have relatively large implications on not only the accuracy of EPCs in uninsulated homes, but also on ceiling retrofit payback calculations for UK homes.

The suspended timber ground floor insulation had a more modest performance and resulted in a modelling gap of 0.19 W/(m²·K) and 0.23 W/(m²·K). The cause of this is not known, though the home had only a small section of suspended timber ground floor and a much larger area of solid ground floor. This prevented the suspended timber ground floor from being cross ventilated, as it only had air bricks along the one façade (front). More research is needed to understand how suspended timber ground floor thermal performance is affected by single-sided versus cross sub floor ground void ventilation and how this impacts the savings achieved by retrofitting.

3.2.1 Contribution of individual elements to plane element fabric heat loss (HTC_f)

Table 3-3 shows the impact the improvement in U-values have had on plane element fabric heat loss, i.e. considering the U-values and relative size of heat loss area of each element.

Table 3-3 Impact of retrofit on fabric plane element heat loss (excluding thermal bridging)

Element	Pre-retrofit (W / K)	*Proportion of heat loss Pre-retrofit*	Post-retrofit (W / K)	*Proportion of heat loss Post-retrofit*
External walls	130	*59 %*	54	40 %
Floor	38	*17 %*	32	24 %
Roof	19	*9 %*	14	10 %
Windows and doors[13]	33	*15 %*	33	25 %

As can be seen, despite the significant reduction in U-value, external walls remain the most significant element, still responsible for 40 % of plane element fabric heat loss, while the other elements, apart from the roof, become relatively more important.

The windows and doors (which were not replaced) became responsible for a particularly large share of the overall plane element fabric heat losses after the other elements were replaced, being responsible for around a quarter of all plane element fabric heat losses on this house following retrofit.

The windows and doors were deemed to be in relatively good condition and not included in the whole house approach to the retrofit of 56TR, since it is not likely a landlord would replace windows that are in good condition. However, it is important to note that no manufacturer's literature could be obtained for the windows and doors and so RdSAP default values were used in this calculation of plane element fabric heat losses. It is possible therefore that the heat losses through these elements were lower than that measured via the centre pane.

As can be seen in Figure 3-11 the absolute savings achieved by the external wall insulation far outweigh the combined savings from the rest of the fabric improvements. This suggests that concentrating on improving the U-values of solid external walls has by far the greatest potential to reduce the plane element heat losses in homes like 56TR.

Figure 3-11 also highlights the performance and modelling gap measured in the homes. RdSAP defaults predict the pre- retrofit HTC_f to be higher and the post-retrofit HTC_f to be lower than that which was measured. This means that the EPC model suggests that the retrofits will reduce HTC_f by almost 60 %, while the measured U-values suggest this value is significantly lower at around 40 %.

[13] Estimated U-values

The implication of this is that retrofit savings predicted by EPCs may not be realised in homes like 56TR, which could be a problem for pay-as-you-save or perceptions of the benefits of retrofitting homes. Despite this, the findings also illustrate that even where there are relatively large performance/modelling gaps, substantial reductions in plane element fabric heat loss can still be achieved by SWI (either EWI, IWI or a combination of the two) in dwellings where the dominant heat loss area is the external walls and where the walls have yet to be insulated.

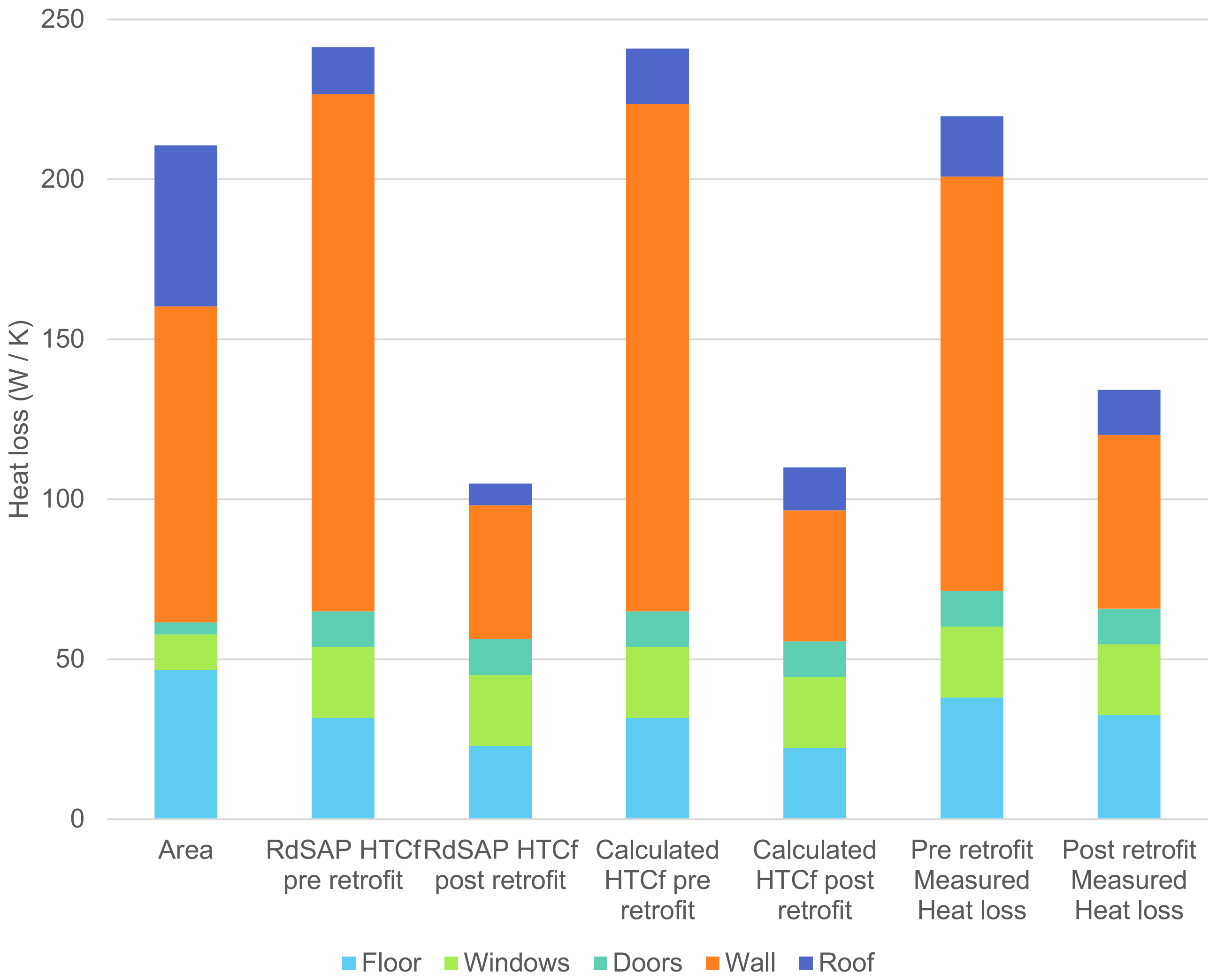


Figure 3-11 Heat loss of fabric elements pre and post-retrofit, according to heat flux measurements

U-value improvement summary

The improvement in the external wall U-values more than halved the predicted plane element fabric heat losses in the home, with most of the savings coming from the IWI and EWI hybrid retrofit. However, the measured savings were slightly lower than the predictions, with RdSAP predicted performance gaps of between 16 % and 259 % for the IWI and 53 % for the EWI (i.e. the baseline walls had lower heat loss and the retrofitted walls had higher heat loss than was predicted). This shows the impact that using RdSAP U-value defaults (that are not reflective of a home's actual plane element fabric heat loss) can have on the accuracy of predicted retrofit savings in models.

The EWI achieved a U-value reduction of (0.9 ± 0.11) W/(m²·K). The IWI reductions ranged from (0.32 ± 0.36) W/(m²·K) where TIWI was already present, up to (0.99 ± 0.13) W/(m²·K) where there was no TIWI. Large variability in U-values was noted across elements, in part believed to be due to inhomogeneous construction profiles and varying moisture content. Solar radiation may have also affected U-values obtained from south facing elements, though the degree to which this was occurring is unknown.

The assumed age-band related RdSAP default U-values were similar to those calculated using the BRE U-value calculator, though these were generally overestimates compared with measured values for the external walls and suspended ground floor, and underestimates for the solid ground floor and ceilings.

Target U-values for sloping ceilings may be unlikely to be achieved for 'skeiling' constructions, since there is often likely to be insufficient space to install insulation (due to the lack of head height), thus bespoke solutions and target U-values are needed for this feature in homes. However, as RdSAP assumes that these areas are insulated, there is potential for considerable savings if they are, in fact, uninsulated, which is not uncommon.

Post-retrofit, the existing double glazed windows and composite doors were predicted to be responsible for up to 25 % of the plane element fabric heat losses in the home, however, this is likely to be an overestimate since these are based on default U-values for homes of this age, while this home had had a previous double glazing retrofit.

This suggests that there is a need for a greater range of default values to capture the variation in window and door thermal performance, especially as these elements often account for a significant proportion of the dwellings overall heat loss area. Consequently, they can have a big impact on model accuracy for homes that have been retrofitted.

3.3 Whole house heat loss (HTC) improvement

The total measured heat losses from the base case dwelling and retrofits are shown in Table 3-4"; the cumulative benefit of the retrofits has reduced the HTC by (82 ± 20) W/K (37 ± 9) %. The hybrid SWI had the biggest reduction on HTC, despite the uncertainty associated with this test being relatively high. In contrast, there was no measurable improvement from the loft, ground floor or whole house retrofits since the measured change was within the uncertainty of the tests undertaken. Despite this, when taken as a cumulative impact, the combined retrofits added substantially to the SWI only improvements.

Table 3-4 Test house HTC after each retrofit stage

Retrofit	HTC (W/K)	HTC uncertainty	HTC reduction (W/K)	Percentage reduction
56TR.B Base case	219 ± 15	7 %	n/a	n/a
56TR.R Loft insulation	208 ± 6	3 %	11 ± 16.5	(5 ± 8) %
56TR.R.F Suspended timber ground floor	223 ± 13	6 %	-15 ± 14.5	(-7 ± 7) %
56TR.R.F.W IWI & EWI hybrid	161 ± 26	16 %	62 ± 29.5	(28 ± 13) %
56TR.R.F.W.WH Whole house approach *(Insulation below DPC & insulation added to sloping ceiling)*	137 ± 13	9 %	23 ± 29.2	(15 ± 18) %
Cumulative reduction			***82 ± 20***	***(37 ± 9) %***

The large uncertainty reported for the IWI & EWI stage is due to the weather station data feed for solar radiance dropping out during the coheating test for the IWI & EWI hybrid retrofit. Solar irradiance was therefore inferred from heat flux density measurements from a HFP plate attached to a window. This method of assessing solar is less accurate, and the uncertainty in the HTC is, thus, larger.

The improvements achieved by each retrofit stage are illustrated in Figure 3-12 showing the coheating test results which were used in the analysis to evaluate the success of the retrofits. As can be seen the ground floor, loft, and whole house approach retrofits individually result in no significant change in the HTC, while the cumulative retrofits add up to a significant improvement in the home.

2.03 DEEP 56TR

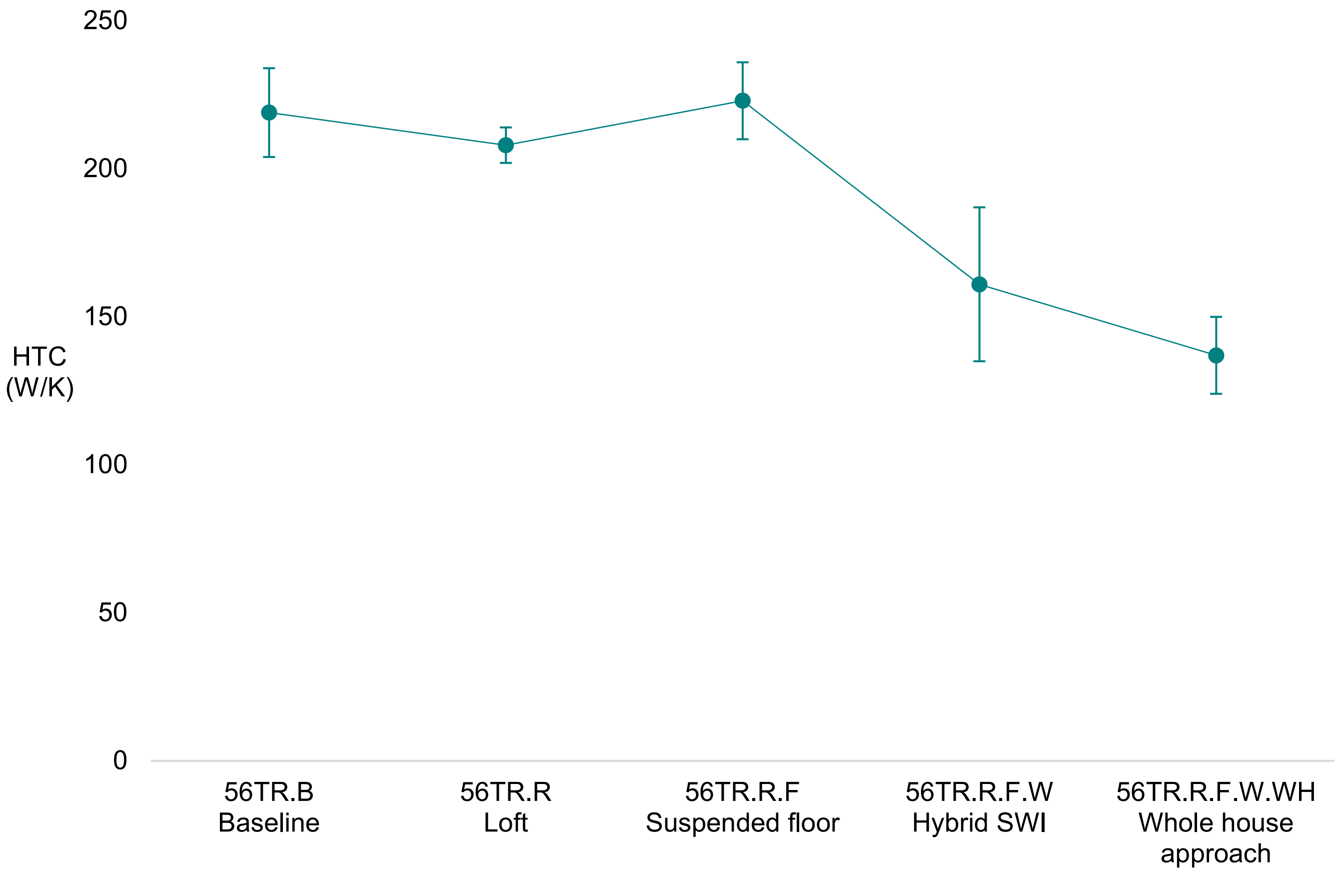


Figure 3-12 Coheating HTC at each retrofit stage

3.3.1 Ventilation heat loss reductions; 56TR.A

To approximate the heat loss attributable to the airtightness improvements, the n / 20 'rule of thumb' can be used in accordance with Equation 1.

Equation 1 Estimating ventilation heat loss (HTC_v) via the n / 20 rule

$$HTC_v = \left(\frac{Permeability\ (m^3\ per\ m^2.hr\ @50\ pa) \times Volume\ (m^3)}{20\ \div\ specific\ heat\ capacity\ of\ air\ (3\ MJ\ /\ m^3K)} \right) \times Shelter\ factor\ (0.85)$$

As previously mentioned, the retrofits had no measurable impact on the airtightness of the home, meaning that air leakage was responsible for around 29 W/K pre and 32 W/K post-retrofit each stage of the retrofit.

This illustrates that as the fabric of homes is insulated, the relative importance of air leakage increases. For instance, 56TR was relatively airtight, with an airtightness of around 8 $m^3/(h{\cdot}m^2)$ @ 50Pa. Pre-retrofit, this accounted for ~10 % of heat loss (according to the n/20 rule-of-thumb). Post-retrofit, the fabric improvements meant that the air leakage became responsible for ~17 % of heat loss.

Currently, measures to reduce air leakage are not part of domestic energy efficiency policy, though this may become a more important heat loss area in the future.

3.3.2 Roof heat losses; 56TR.R

The first fabric retrofit undertaken on this dwelling was to increase the levels of loft insulation, however, this did not result in a measurable reduction in HTC. This may be because the existing loft insulation in the base case scenario was already well installed and providing a decent amount of thermal resistance. Replacing this with new and additional levels of loft insulation means that, due to diminishing returns, this did not significantly reduce the overall plane element heat loss.

The contractor mistakenly omitted the installation of an insulated and sealed loft hatch from the loft retrofit stage. This is standard practice and should have been completed, but it was only noticed at the end of the project. The impact of insulating and sealing the hatch was therefore not captured by any of the tests performed. The results here are potentially underestimating the benefit that loft retrofits can achieve.

Many lofts have imperfectly fitted loft insulation. Reasons include: being impacted by the storage of household items; disturbance during access to maintain services; and often having areas inaccessible to insulation, especially at the roof eaves. Other DEEP case studies observed these issues, but 56TR roof did not have many of these features, which possibly explains why a saving could not be measured. More investigations of a broader range of loft and house types are needed to understand how much benefit can be achieved from replacing loft insulation.

3.3.3 Suspended timber ground floor heat losses; 56TR.F

Suspended floor insulation was installed as shown in Figure 3-13.

Figure 3-13 Suspended floor insulation

No measurable change in HTC was observed following the suspended timber ground floor retrofit. Conversely, there was a slight increase in HTC, though this was within the uncertainty of the test. This may be because the home had a part suspended and part solid ground floor, which meant the area being insulated was relatively small, only 8 % of the total heat loss area of the house. Also, the sub floor void was not cross ventilated, as only air bricks were installed on one façade of the dwelling. This may have further affected the expected heat transfer pre-retrofit, measuring lower than would otherwise be the case.

Having a hybrid floor like this is relatively common in the UK, particularly in older terraced homes. Further investigations into the benefit of insulating different ground floor types in different house types is needed to fully understand the potential impact that suspended ground floor insulation may have on UK homes.

3.3.4 External wall heat losses; 56TR.W

EWI was installed on the gable wall, while IWI was installed on the front and rear of the home, as shown in Figure 3-14 and Figure 3-15.

Figure 3-14 Blown mineral wool and brick effect panels EWI being fitted to the gable wall

Figure 3-15 Wood fibre IWI being fitted on the front and rear wall

This hybrid SWI resulted in a saving of (62 ± 30) W/K in HTC or (28 ± 13) %. This was by far the greatest single improvement made to the house, which is perhaps not surprising given that the external walls represented 47% of the total heat loss area pre-retrofit.

There was already TIWI installed in several rooms in the house, meaning that owing to the laws of diminishing returns, the saving would be even greater in homes without TIWI present.

IWI is a relatively complex retrofit and can have several unintended consequences for the house and for neighbouring properties. Additionally, the interactions of IWI and EWI in a hybrid retrofit are not well understood. These issues are further explored in Section 3.4.

3.3.5 Whole house approach; 56TR.E

The activities undertaken in the whole house approach retrofits stage were to insulate the sloping roofs, including an area of ceiling where there was a false dormer feature, and to extend EWI (75 mm of XPS foam to avoid moisture issues) under the DPC. These are activities that are commonly omitted from retrofits. Sloping ceilings are neither classed as external walls nor lofts, meaning they are often an area that is not improved during either external wall or loft retrofits. Additionally, these areas are also technically difficult to access, requiring ceilings to be removed. This causes large amounts of disruption for the householder.

Insulation below the DPC is routinely omitted from EWI, since there is a reluctance to install any materials under the DPC in order to avoid rising damp. Additionally, the previous guidance was to continue the insulation 400 mm below the finished ground level, which would be costly, disruptive, and time consuming. This was another barrier to the insulation below the DPC being installed.

Guidance has recently changed to allow contractors to simply extend the DPC insulation to the finished ground level and so this was undertaken in this case study along the gable wall. The DPC is intended to reduce moisture risk associated with the thermal bridge at the floor - wall junction though it may also have an impact on floor heat losses.

PAS2035 attempts to encourage these retrofit activities to take place alongside other retrofits and so this test phase was designed to understand if there are likely to be any benefits in terms of heat loss reductions associated with these often omitted activities. The coheating test did not measure a statistically significant reduction in HTC following this retrofit stage, though it is thought this was likely to be due to the large uncertainty related to the loss of solar data in the preceding hybrid wall retrofit coheating test.

Insulating the sloping roof and DPC resulted in a (24 ± 29) W/K, or (15 ± 18) % reduction in HTC, which is not significant, particularly given the uncertainty associated with the measurement. The improved sloping roof U-value suggests the HTC reduction may be in the region of 5 W/K, though the quality of installation of the pre-existing sloping roof insulation was poor, as seen in Figure 3-3, so this may be a conservative underestimate. It is not known by how much the below DPC might have impacted on the overall HTC. Even though a significant reduction for this single stage was not achieved, as can be seen in Figure 3-16, when added to the cumulative savings the combined retrofits reduced the HTC by (82 ± 20) W/K (39 ± 9) %.

2.03 DEEP 56TR

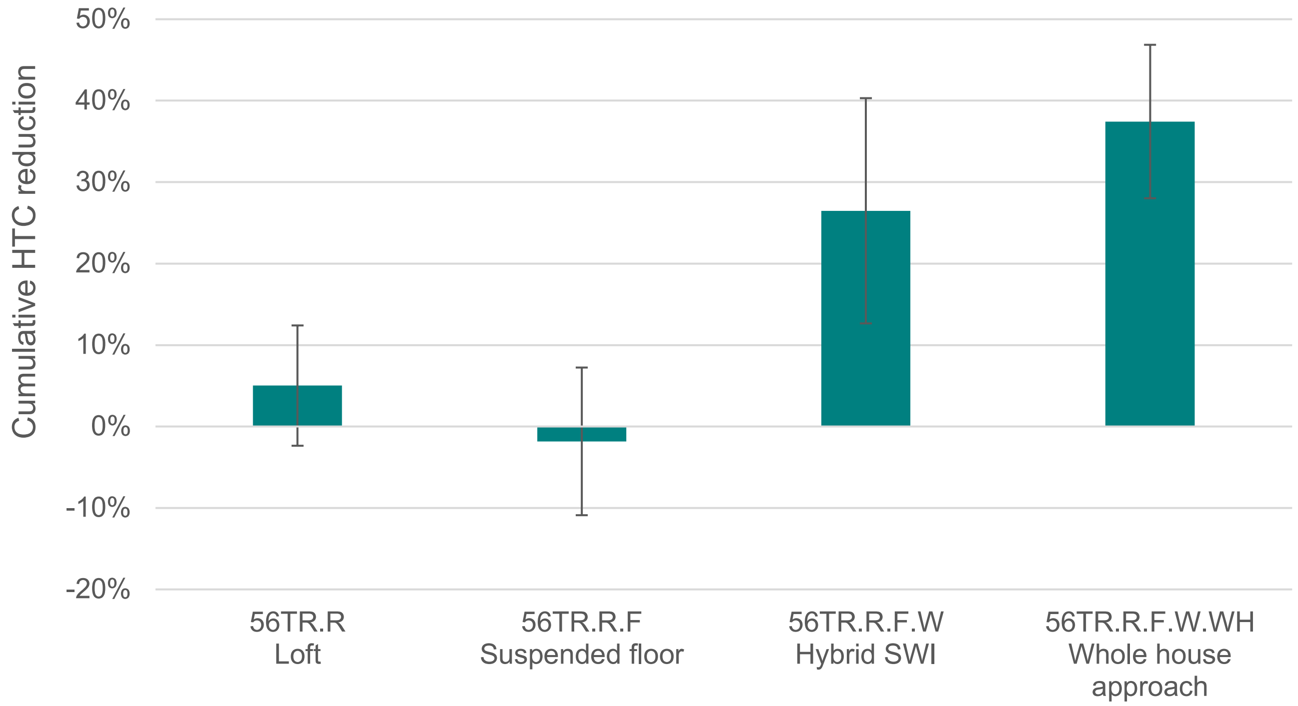


Figure 3-16 Cumulative HTC savings achieved by retrofits

3.3.6 QUB versus coheating test HTC results

In total nine QUB tests were performed on 56TR across 3 different retrofit stages. Out of these nine, one was discounted based on the test α value (a ratio of power input, temperature difference, and the HTC of the property) being outside of the recommended limits. A further test was discounted due to a technical error resulting in one of the QUB heaters not operating; hence only tests from two retrofit stages are presented. The tests completed in the suspended floor stage had a duration of 10 hours and were completed in January 2021. The tests completed in the whole house phase had a duration of 8 hours and were completed in April 2021.

The results of the remaining seven tests are shown in Figure 3-17, compared against the upper and lower uncertainty limits of the measured coheating HTC, which are represented by dotted lines. It is important to note that, despite the house being semi-detached, the results presented in this figure do not take into consideration any adjustments made for party wall heat losses.

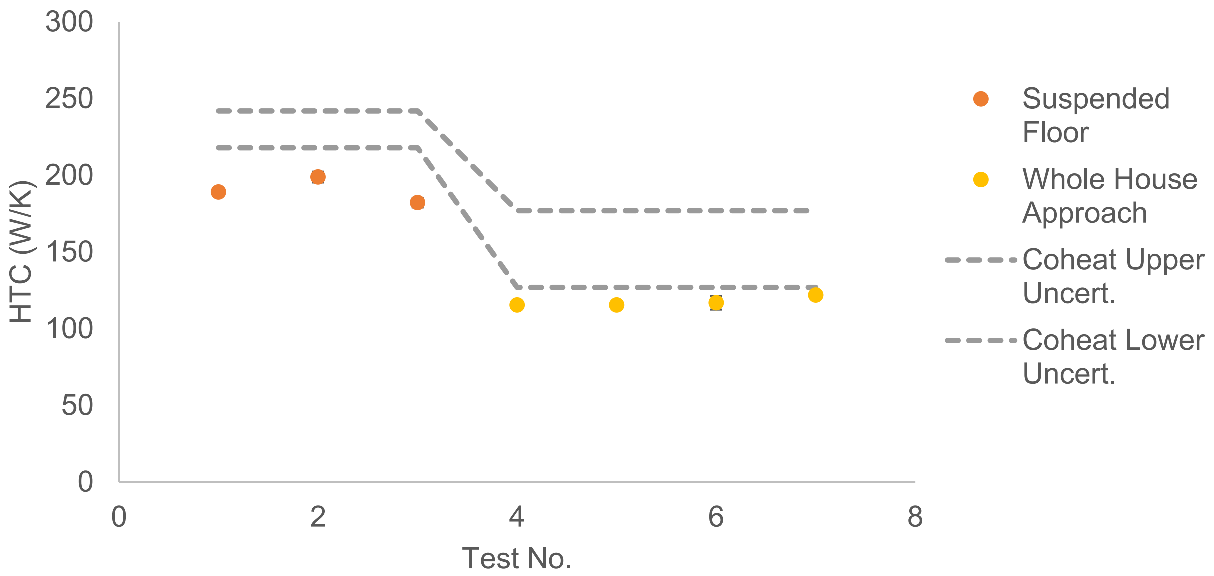


Figure 3-17 56TR QUB test measurements

It is clear from Figure 3-17 that all of the tests are lower than the coheating HTC and outside of the associated uncertainty boundaries.

The tests performed show good repeatability. All tests were within 6 % and 9 % of the weighted average for the suspended floor and whole house approach retrofit stages respectively. The uncertainty weighted average of the two stages where QUB tests were completed are shown in Figure 3-18.

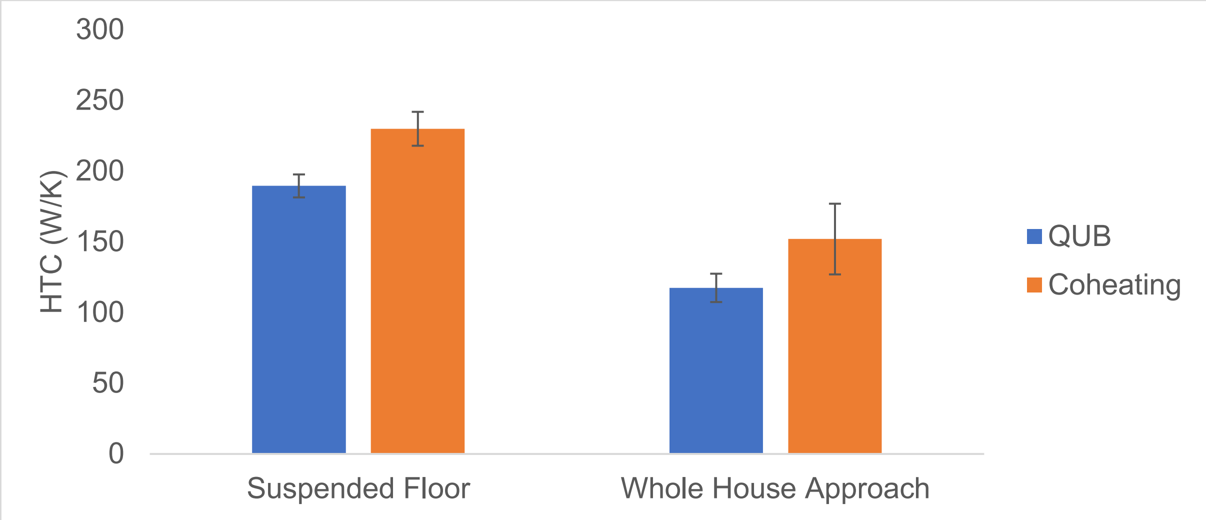


Figure 3-18 Average QUB measurements compared against coheating

As with the individual tests, these average values are less than the corresponding HTC measured through coheating. The uncertainty boundaries do not overlap for any of the configurations. The weighted average QUB values are closer to the coheating measurements for the suspended floor stage than the whole house stage. Relative differences of 18 % and 24 % for ground floor and whole house stages respectively were recorded.

The cause of these differences could include differing heat flow patterns through elements that do not face the external environment, such as party walls. Additionally, the larger temperature difference present in the coheating test may be resulting in larger infiltration losses occurring. Further investigation is required to determine the cause of the difference between the HTC measurements and the suitability of QUB for properties of this type.

Whole house heat loss improvement summary

This section shows that the retrofits reduced the HTC of the home by (82 ± 20) W/K (37 ± 9) %. Almost all this improvement was due to the hybrid IWI and EWI retrofits, reducing the HTC by (62 ± 30) W/K (28 ± 13) %. The loft had no measurable impact on the HTC as it was already insulated to some degree. It may have reduced some other benefits, for example, removing thermal bridges and condensation risks, which will be explored in the following section.

Similarly, the suspended ground floor retrofit did not make a measurable change in HTC, perhaps as an airtightness membrane was not installed and it was only 8 % of the heat loss area (most of the ground floor was solid) to begin with. Furthermore, it is not known how much ventilation occurred in the sub floor void as it had no cross ventilation. More investigations into the benefits of suspended ground floor insulation in different house and floor types is needed.

None of the retrofits had a significant impact on infiltration and heat loss associated with air leakage, though the final whole house stage retrofits may have marginally increased infiltration rates. This is due to the development of shrinkage cracks where the newly plastered sloping ceilings met the existing horizontal ceilings in the upstairs rooms, coupled with the new insulation potentially being inadequately sealed at the edges, therefore compromising its ability to form an effective air barrier.

3.4 Thermal bridging heat losses

Thermal bridging at all junctions in 56TR, identified in Figure 3-19 and Figure 3-20 below, was assessed with numerical simulation techniques, using TRISCO software, outputs from which were used to calculate junction Ψ-values and surface temperature factors. Each junction was assessed under uninsulated and retrofitted scenarios. 46 individual junctions were identified in the base case; the large number of junctions is in part due to the partial IWI present in the building and the ground floor utility room offshoot. Resulting Ψ-values would be used to calculate whole building thermal bridging heat transfer coefficient (HTC_b) at each stage. Default material properties were sourced from BS EN ISO 10456-2007 and BR 443.

A brick sample was taken for analysis so that the default value for the thermal conductivity of a solid wall could be compared to the actual thermal conductivity found on site and the implications of any disparity considered.

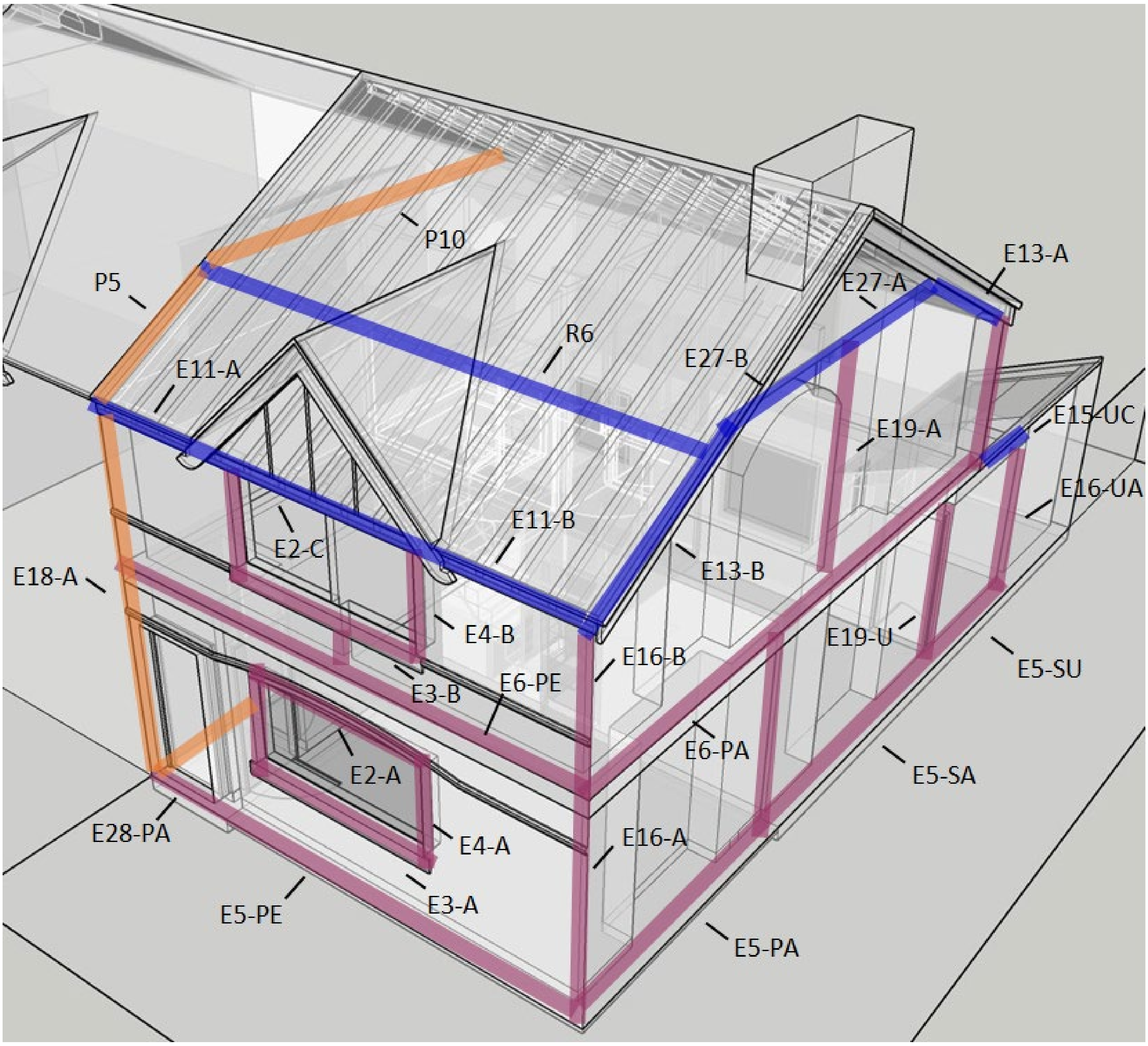


Figure 3-19 Frontal view of 56TR junctions (purple: wall junctions, blue: roof junctions, orange: party junctions)

There are no standard Ψ-values for existing buildings against which calculated values could be directly compared. However, SAP Appendix K publishes these for new build constructions and a comparison with these is presented here to provide a regulatory context. As no default Ψ-values are available for existing buildings, a default y-value from SAP (0.15) is used in RdSAP/EPC calculations to account for thermal bridging heat loss and is compared here with the y-value calculated for 56TR.

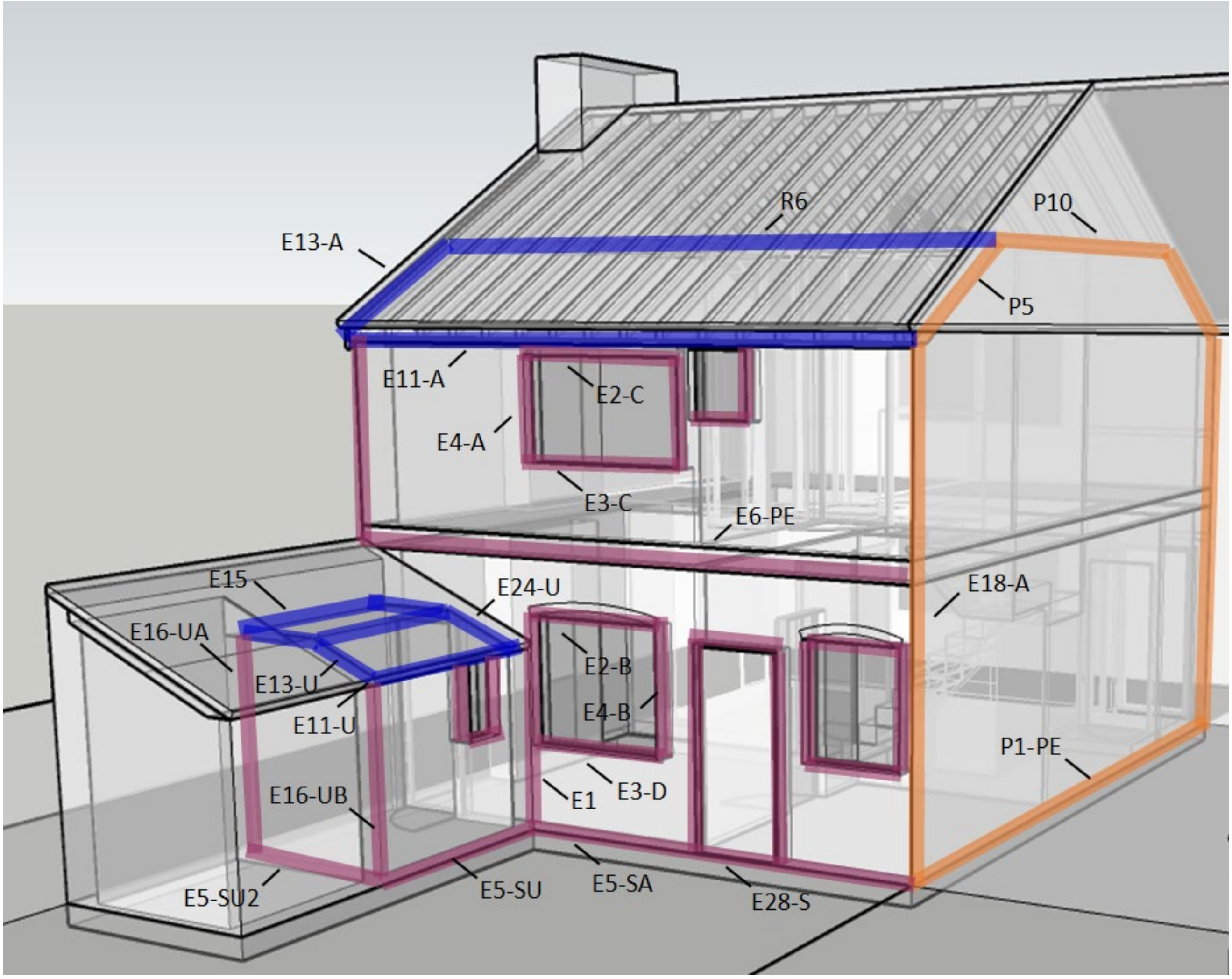


Figure 3-20 Rear view of 56TR junctions assessed, with codes. Purple: wall junctions, blue: roof junctions, orange: party junctions

Each specific junction is described in Table 3-5, and the impact of each retrofit on each junction in terms of heat loss and surface condensation risk is investigated in the following section.

Table 3-5 Table of 56TR junction codes with descriptions

Junction code	Description
E11-A	External wall - eaves
E11-B	External wall, with pre-existing IWI - eaves
E11-U	Utility sloped ceiling - utility external wall
E13-A	Gable wall - sloped eaves
E13-B	Gable wall, with pre-existing IWI - sloped eaves
E13-U	Utility sloped ceiling - outhouse wall
E15-UA	Utility flat ceiling - external wall
E15-UB	Utility flat ceiling - outhouse wall
E15-UC	Utility flat ceiling - gable wall
E16-A	Normal corner, external wall - Gable wall
E16-B	Normal corner, external wall, with pre-existing IWI - gable wall
E16-UA	Gable wall - outhouse wall
E16-UB	Utility external wall - outhouse wall
E17-U	Inverted corner, utility external wall - rear external wall
E18-A	External wall - party wall
E19-A	External wall - internal partition wall
E19-B	Gable wall, with pre-existing IWI - internal partition wall
E19-U	Gable wall - utility doorway partition
E24-U	Utility sloped ceiling - rear external wall
E27-A	Flat ceiling - gable wall
E27-B	Flat ceiling, with pre-existing IWI - gable wall
E28-PA	Suspended ground floor - door threshold
E28-S	Solid ground floor - door threshold
E2-A	Window head - external wall
E2-B	Window head - external wall, with pre-existing IWI
E2-C	Window head - eaves
E3-A	Window sill, stone - external wall
E3-B	Window sill, stone - external wall with pre-existing IWI
E3-C	Window sill, brick - external wall
E3-D	Window sill, brick - external wall with pre-existing IWI
E4-A	Window Jamb - external wall
E4-B	Window Jamb - external wall with pre-existing IWI

E4-U	Window jamb - utility external wall
E5-PA	Suspended ground floor - gable wall, joists parallel
E5-PE	Suspended ground floor - external wall, joists perpendicular
E5-S-A	Solid ground floor - external and Gable wall
E5-SU	Solid ground floor - utility external wall
E5-SU2	Solid ground floor - utility outhouse wall
E6-PA-A	Intermediate floor - gable wall, joists parallel
E6-PA-B	Intermediate floor - gable wall, with pre-existing IWI, joists parallel
E6-PA-C	Intermediate floor - gable wall, with pre-existing IWI, joists parallel
E6-PE-A	Intermediate floor - external wall, joists perpendicular
E6-PE-B	Intermediate floor - external wall, with Pre-existing IWI, joists perpendicular
P10	Flat ceiling - party wall
P1-PE	Ground floor - party wall, joist perpendicular
P5	Party wall - sloped ceiling
R6	Sloped ceiling - flat ceiling

3.4.1 Ψ-values; SAP appendix K vs Thermal simulation

Figure 3-21 compares Ψ-values between Appendix K of SAP and those calculated for 56TR at each stage. As expected, there is no correlation between the calculated values for 56TR and the default values found in appendix K.

The lack of relationship is likely due to the differences in building fabric assumptions and junction build ups, as Appendix K values are based on a typical new build house. Thus, if refined Ψ-values were to form the basis of a revised y-value that can be incorporated into RdSAP, this assessment suggests that Appendix K may not be suitable and an alternative appendix specific to existing solid walled buildings would be needed.

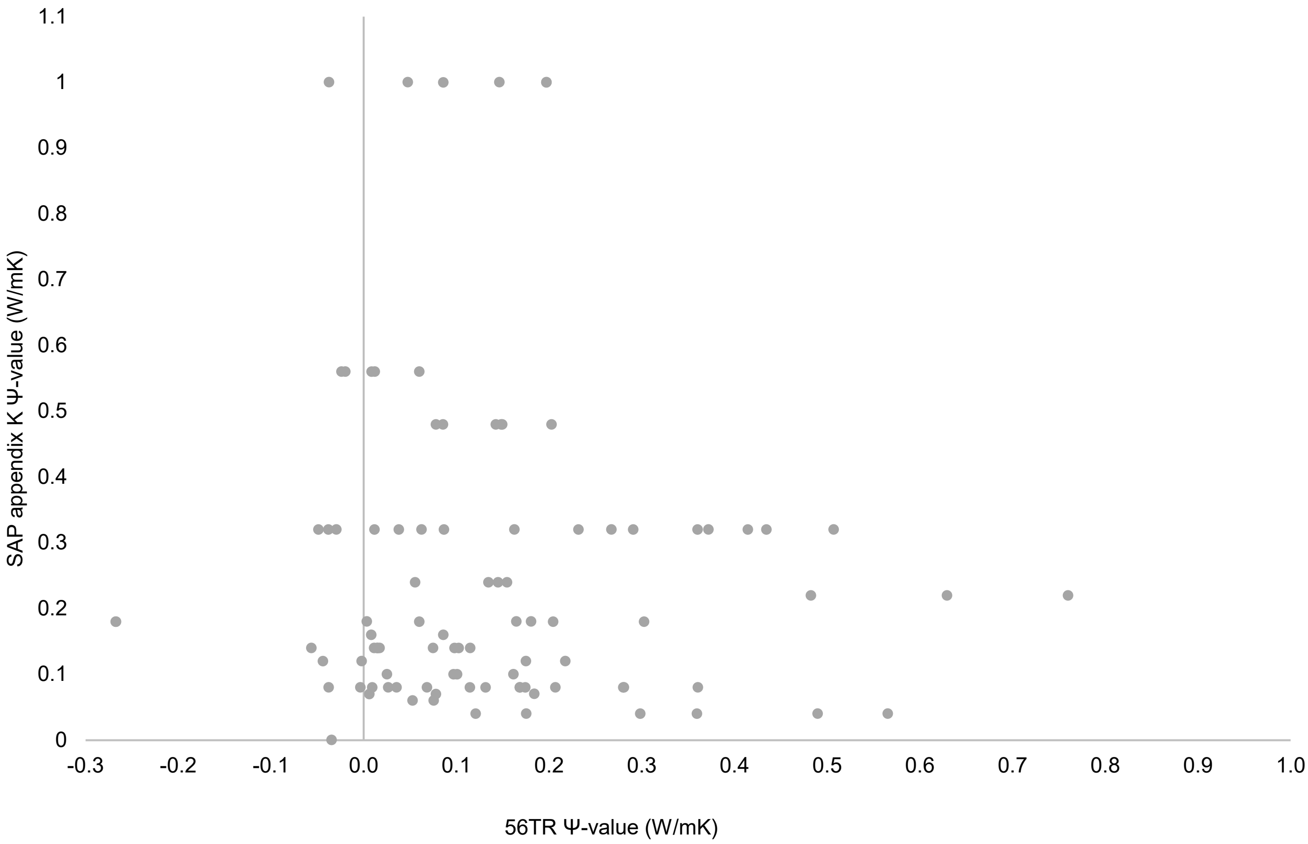


Figure 3-21 Comparison of SAP Appendix K and 56TR Ψ-values

Tabulated Ψ-values for each junction can be found in Table 3-6. Junctions that were found to have a Ψ-value that diverges significantly from the Appendix K value include:

- Window heads: window head junctions have much lower Ψ-values than found in appendix K, which assumes that window lintels have a high Ψ-value of 1 W/(m·K). Window heads in 56TR consist of a brick lintel externally and a timber lintel internally; the low thermal conductivity of timber may explain the difference in Ψ-value.
- Wall junctions: wall junctions resulted in a wide variation in Ψ-values both higher and lower than Appendix K values, this is in part due to the number of variants of each junction due to the partial pre-existing IWI within 56TR.
- Sloped ceiling to flat ceiling: this junction has a significantly higher Ψ-value, due to a band of uninsulated ceiling. This junction will be discussed in greater detail in the following section.

Table 3-6 Table of Ψ-values at each junction at each stage; blank cells indicate no change

Junction	Ψ-value					
	App. K	56TR.B	56TR.R	56TF.F	56TR.W	56TR.WH
External wall - eaves	0.080	-0.038			0.010	0.027
External wall, with pre-existing IWI - eaves	0.080	0.036			0.010	0.027
Utility sloped ceiling - utility external wall	0.080	0.169			0.169	
Gable wall - sloped eaves	0.040	0.175			0.566	0.490
Gable wall, with pre-existing IWI - sloped eaves	0.040	0.121			0.360	0.299
Utility sloped ceiling - outhouse wall	0.560	0.012			0.009	0.121
Utility flat ceiling - external wall	0.560	0.012			0.009	
Utility flat ceiling - outhouse wall	0.560	0.060			-0.019	
Utility flat ceiling - gable wall	0.560	0.060			-0.024	
Normal corner, external wall - gable wall	0.180	0.165			0.303	
Normal corner, external wall, with pre-existing IWI - gable wall	0.180	0.060			0.205	
Gable wall - outhouse wall	0.180	-0.267			0.181	
Utility external wall - outhouse wall	0.180	-0.267			0.004	
Inverted corner, utility external wall – rear external wall	0.000	-0.538			-0.034	
External wall - party wall	0.120	0.218			0.175	
External wall - internal partition wall	0.070	0.078			0.184	
Gable wall, with pre-existing IWI - internal partition wall	N/A	N/A	N/A	N/A	0.006	0.006
Gable wall - utility doorway partition	0.120	-0.044			-0.002	
Utility sloped ceiling - rear external wall	0.240	0.056		0.056	0.155	
Flat ceiling - gable wall	0.480	0.143	0.150		0.203	
Flat ceiling, with pre-existing IWI - gable wall	0.480	0.078	0.086		0.149	
Suspended ground floor - door threshold	0.220	0.483		0.630		
Solid ground floor - door threshold	0.220	0.760				
Window head - external wall	1.000	-0.037			0.048	
Window head - external wall, with pre-existing IWI	1.000	0.086			0.048	

2.03 DEEP 56TR

Window head - eaves	1.000	0.197				0.147
Window sill, stone - external wall	0.080	0.361			0.175	
Window sill, stone - external wall with pre-existing IWI	0.080	0.280			0.115	
Window sill, brick - external wall	0.080	0.068			0.115	
Window sill, brick - external wall with pre-existing IWI	0.080	0.132			0.115	
Window Jamb - external wall	0.100	0.097			0.162	
Window Jamb - external wall with pre-existing IWI	0.100	0.162			0.101	
Window jamb - utility external wall	0.100	0.025			0.101	
Suspended ground floor - gable wall, joists parallel	0.320	-0.038		0.087	0.435	0.360
Suspended ground floor - external wall, joists perpendicular	0.320	-0.049		0.038	0.012	
Solid ground floor - external and Gable wall	0.320	0.372			0.415	0.163
Solid ground floor - utility external wall	0.320	0.268			0.063	0.232
Solid ground floor - utility outhouse wall	0.320	-0.029			0.063	
Intermediate floor - gable wall, joists parallel	0.140	0.115			0.012	
Intermediate floor - gable wall, with pre-existing IWI, joists parallel	0.140	0.103			0.015	
Intermediate floor - gable wall, with pre-existing IWI, joists parallel	0.140	0.075			0.015	
Intermediate floor - external wall, joists perpendicular	0.080	0.115			0.017	
Intermediate floor - external wall, with pre-existing IWI, joists perpendicular	0.320	0.012			0.017	
Flat ceiling - party wall	0.240	0.145	0.135			
Ground floor - party wall, joist perpendicular	0.160	0.086		0.008		
Party wall - sloped ceiling	0.080	0.281				0.207
Sloped ceiling - flat ceiling	0.060	2.695	0.076			0.053

3.4.2 Thermal bridging heat loss: HTC_b change by retrofit

Absolute heat loss from a thermal bridge (HTC_b) is calculated by multiplying the Ψ-value by the length of a junction. Figure 3-22 shows the change in HTC_b for individual junctions, comparing post-retrofit values with the pre-retrofit baseline case.

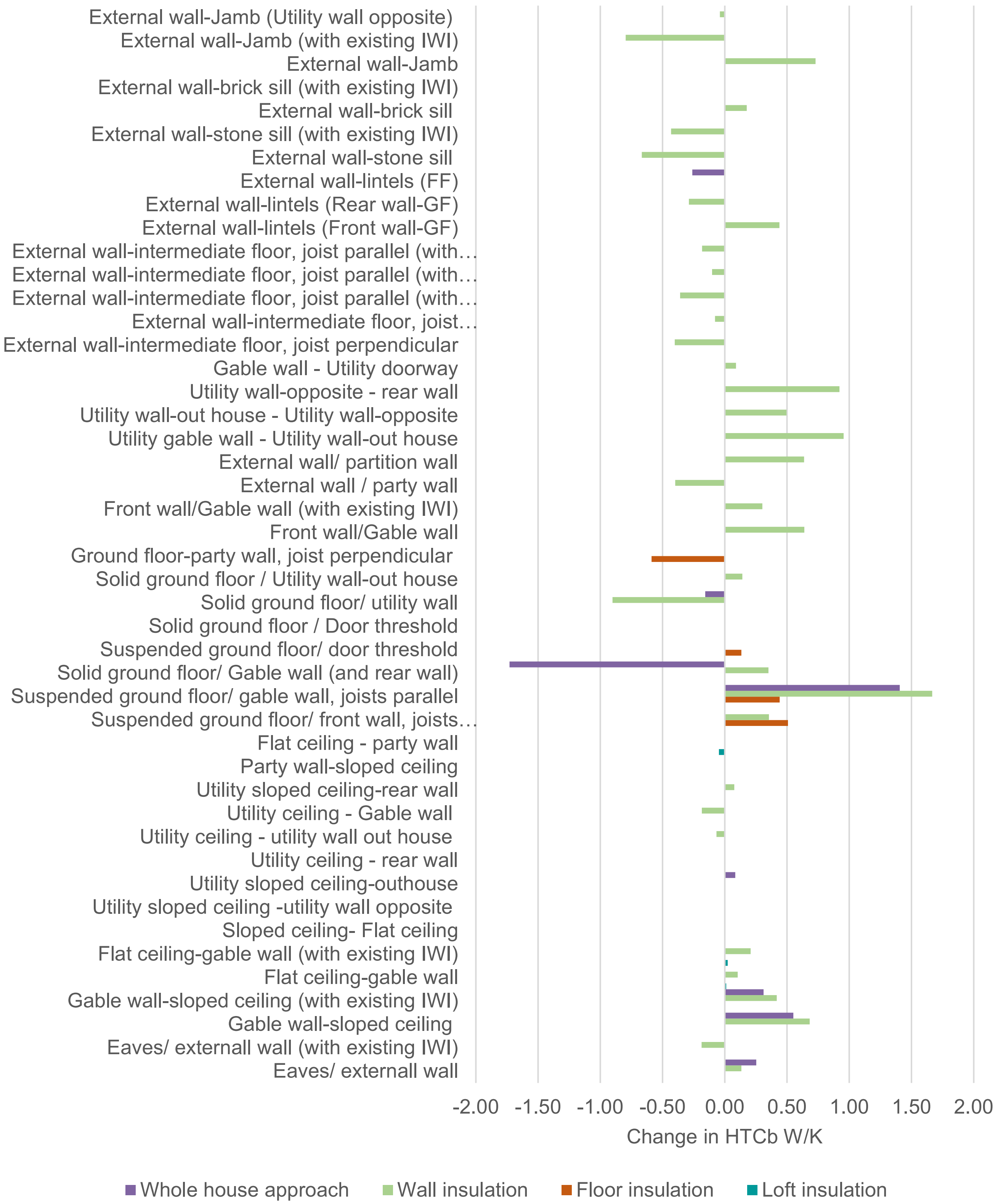


Figure 3-22 change in HTC_b per junction for each retrofit stage (flat ceiling – sloped ceiling junction omitted for clarity)

Figure 3-22 show that following the retrofit stages, HTC_b both increased and decreased depending on the junction. It was observed that:

- At junctions around openings and intermediate floor junctions, HTC_b decreased in the majority of cases. This is due to continuous insulation coverage at these junctions.
- At junctions between external wall elements, HTC_b increased marginally with the introduction of the solid wall insulation. This is due to the combination of IWI and EWI creating discontinuities in the insulation layer. This may have been resolved had the IWI been returned on the EWI on the gable wall, though the losses are insignificant.
- Ground floor to external wall junctions experienced an increase in HTC_b in most cases, with both the ground floor and external wall insulation retrofits. The introduction of insulation stripping below DPC level on the gable wall reduced the HTC_b at the junctions between the gable wall and suspended ground floor and the solid ground floor.
- A significant reduction in HTC_b of 31.7 W/K occurred following the loft insulation retrofit, due largely to the addition of insulation to the sloped ceiling to flat ceiling junction where it was missing in the base case, shown in Figure 3-23 and Figure 3-24. The remaining loft junctions underwent minor reductions in Ψ-value.

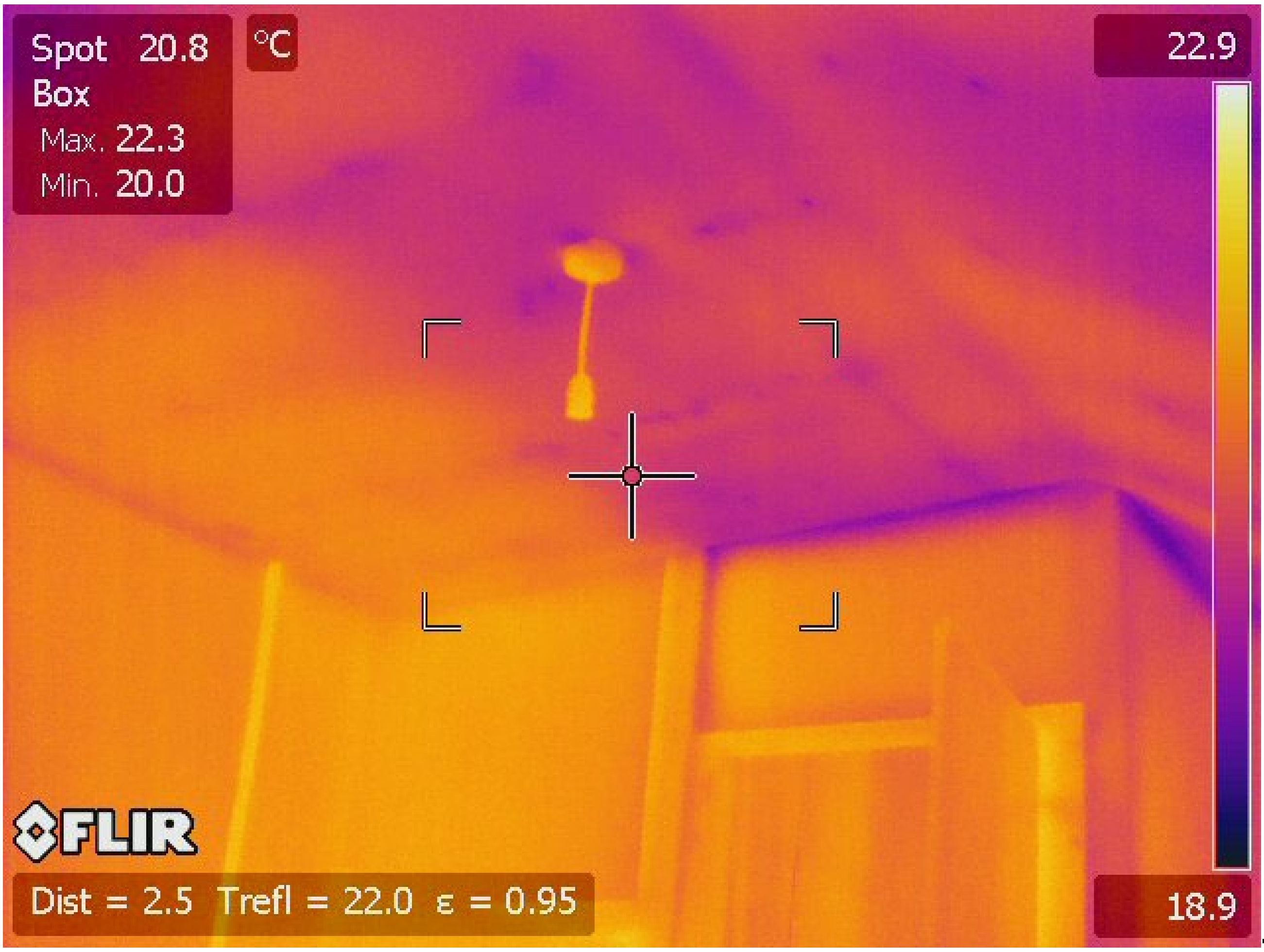


Figure 3-23 Thermal image of sloped ceiling - flat ceiling junction: cold area visible where insulation is missing due to obstructing perlin in roof structure

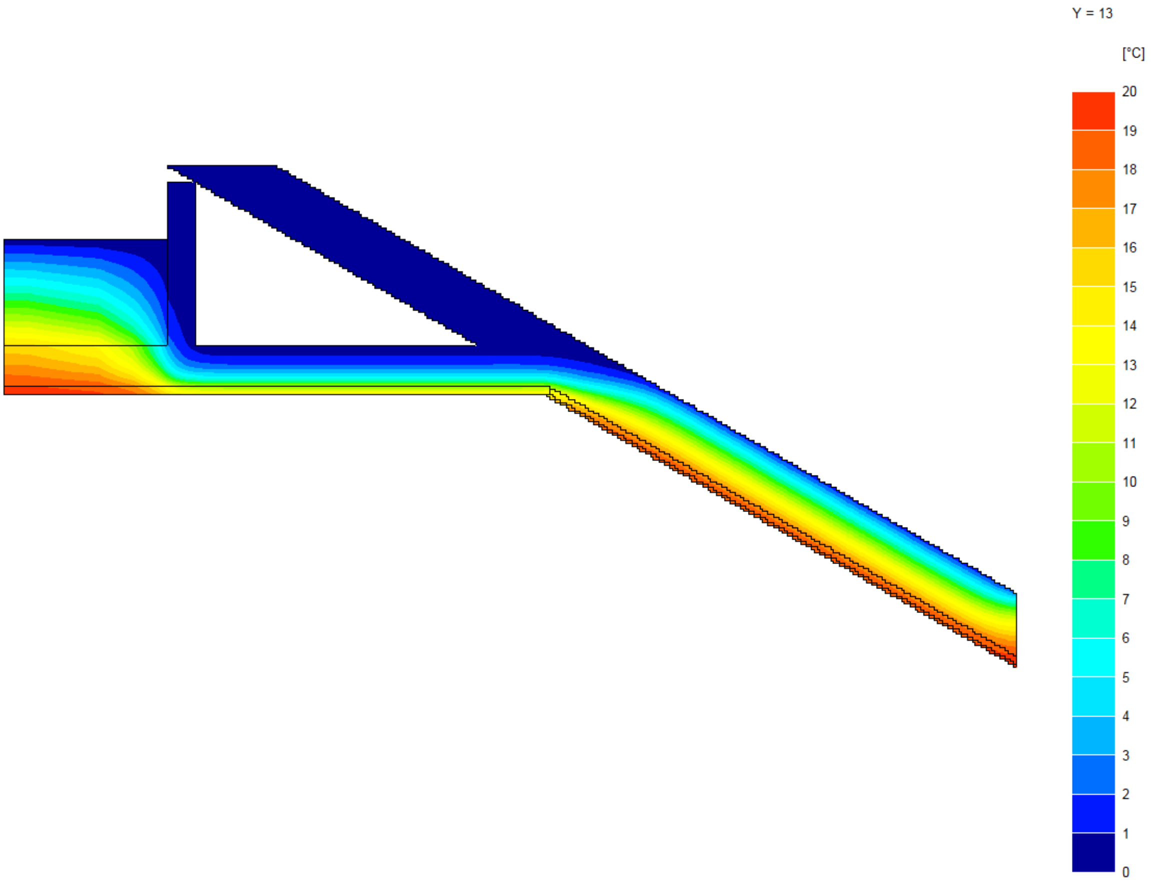


Figure 3-24 Temperature distribution output from numerical thermal simulation of sloped ceiling - flat ceiling junction

3.4.3 Thermal bridging heat loss: y-values

RdSAP and EPCs do not use HTC_b to attribute heat loss for non-repeating thermal bridges (repeating thermal bridges are already included within U-values), instead they use a simplified thermal bridging factor, called a y-value, applied to the entire external heat loss area of a building. The default y-value in RdSAP is 0.15. These y-values are calculated as the sum of HTC_b for all junctions, divided by the total heat loss area (i.e. excluding the party wall). It is therefore possible to generate a y-value from the calculated HTC_b values derived from simulation pre- and post-retrofits for 56TR and compare these with the 0.15 default.

HTC_b and y-values for 56TR are shown in Table 3-7. The default value of 0.15 underestimates heat loss in the pre-retrofit state, but overestimates heat loss due to thermal bridges in all subsequent stages. More research would be needed to investigate if this scenario is common to different building types. However, it suggests that it may be appropriate to develop different default y-values for insulated and uninsulated homes, to improve the accuracy of EPCs, and the accuracy of improvement option evaluations (e.g. under PAS 2035) for retrofit.

When a whole house approach was undertaken, heat loss from non-repeating thermal bridges was reduced by over 50 %. The greatest reduction in non-repeating thermal bridging heat loss occurs after the loft insulation, eliminating the severe thermal bridge due to missing insulation at the sloped ceiling – flat ceiling junction. Ground floor and external wall insulation stages result in minor increases in HTC_b due to discontinuities in the insulation layer between insulation retrofits. The whole house stage reduced the overall HTC_b as it remedied some of the discontinuities introduced in previous stages.

Rerunning the calculations with the actual conductivity derived from the brick sample taken from the house, compared to the default value used in the software, made only a marginal difference to the HTC_b and y-values. More research would be needed to understand if the brick properties in the software are representative of other brick types in the UK.

Table 3-7 HTC_b and y-values for each stage of 56TR retrofit, including values calculated with default brick thermal properties and measured brick thermal properties

Retrofit stage	HTC_b (W/K)		y-value	
	Default properties	Measured properties	Default properties	Measured properties
56TR.B Base case	50.0	50.3	0.24	0.24
56TR.R Loft insulation	19.3	19.6	0.09	0.10
56TR.R.F Suspended timber ground floor	21.9	22.1	0.11	0.11
56TR.R.F.W IWI & EWI hybrid	23.3	27.3	0.11	0.13
56TR.R.F.W.WH Whole house approach *(Insulation below DPC & insulation added to sloping ceiling)*	21.1	25.1	0.10	0.12

3.4.4 Surface temperature factor analysis

Thermal bridges also pose problems in the form of cold surfaces and surface condensation risk in homes. Temperature factors were used to indicate whether a location is at risk of surface condensation. A temperature factor below the critical value of 0.75 is deemed to be at risk. The temperature factor (f_{Rsi}) is calculated using Equation 2:

Equation 2 Temperature factor calculation method

$$f_{Rsi} = \frac{T_{si} - T_e}{T_i - T_e}$$

Where: T_{si} is internal surface temperature (°C)

T_e is external air temperature (°C).

T_i is internal air temperature (°C).

Each numerical thermal simulation performed output a minimum internal surface temperature in addition to heat flow, which was used to perform the temperature factor calculation using Equation 2.

Table 3-8 shows the temperature factor (f_{Rsi}) of the 46 junctions modelled for each retrofit stage. The junctions with f_{Rsi} below 0.75 are highlighted red, indicating they may be at risk of surface condensation.

Table 3-8 Temperature factors at each junction by retrofit stage, red indicates a condensation risk

Element	Junction category	Base case	Loft	Floor	Walls	PAS
Roof	External wall - eaves	0.765			0.880	0.884
	External wall, with pre-existing IWI - eaves	0.867			0.880	0.884
	Utility sloped ceiling - utility external wall	0.761			0.824	
	Gable wall - sloped eaves	0.663			0.714	0.709
	Gable wall, with pre-existing IWI - sloped Eaves	0.735			0.761	0.814
	Utility sloped ceiling - outhouse wall	0.820			0.856	
	Utility flat ceiling - external wall	0.820			0.856	
	Utility flat ceiling - outhouse wall	0.699			0.858	
	Utility flat ceiling - gable wall	0.699			0.814	
	Utility sloped ceiling - rear external wall	0.341			0.744	

	Flat ceiling - gable wall	0.681	0.683		0.857	0.857
	Flat ceiling, with pre-existing IWI - gable wall	0.775	0.777		0.876	
	Sloped ceiling - flat ceiling	0.618	0.913			0.930
	Party wall - sloped ceiling	0.793				0.816
	Flat ceiling - party wall	0.890	0.902			
Wall	Normal corner, external wall - Gable wall	0.609			0.740	
	Normal corner, external wall, with pre-existing IWI - Gable wall	0.781			0.814	0.814
	Gable wall - outhouse wall	0.667			0.797	
	Utility external wall - outhouse wall	0.668			0.840	
	Inverted corner, utility external wall - rear external wall	0.801			0.827	
	External wall - party wall	0.740			0.802	
	External wall - internal partition wall	0.744			0.801	
	Gable wall, with pre-existing IWI - internal partition wall	0.744			0.955	
	Gable wall - utility doorway partition	0.750			0.952	
Windows/ openings	Window head - external wall	0.765			0.919	
	Window head - external wall, with pre-existing IWI	0.878			0.919	
	Window head - eaves	0.740				0.927
	Window sill, stone - external wall	0.652			0.915	
	Window sill, stone - external wall with pre-existing IWI	0.869			0.919	
	Window sill, brick - external wall	0.765			0.919	
	Window sill, brick - external wall with pre-existing IWI	0.878			0.919	
	Window Jamb - external wall	0.662			0.847	
	Window Jamb - external wall with pre-existing IWI	0.649			0.847	
	Window jamb - utility external wall	0.708			0.847	
Floor	Suspended ground floor - door threshold	0.341		0.286		

	Solid ground floor - door threshold	0.347				
	Suspended ground floor - gable wall, joists parallel	0.719		0.705	0.784	0.813
	Suspended ground floor - external wall, joists perpendicular	0.718		0.706	0.828	
	Solid ground floor - external and Gable wall	0.703			0.698	0.780
	Solid ground floor - utility external wall	0.694			0.725	0.771
	Solid ground floor - utility outhouse wall	0.734			0.725	
	Intermediate floor - gable wall, joists parallel	0.728			0.947	
	Intermediate floor - gable wall, with pre-existing IWI, joists parallel	0.771			0.943	
	Intermediate floor - gable wall, with pre-existing IWI, joists parallel	0.719			0.949	
	Intermediate floor - external wall, joists perpendicular	0.919			0.873	
	Intermediate floor - external wall, with pre-existing IWI, joists perpendicular	0.828			0.873	
	Ground floor - party wall, joist perpendicular	0.931		0.942		

In the pre-retrofit base case, 59 % of the junctions in 56TR were assessed to be at risk of surface condensation formation, with a large portion of the ground floor junctions and external wall junctions being deemed to be a condensation risk. After the final whole house retrofit, 15 % of these junctions were a condensation risk.

The introduction of suspended ground floor insulation increased the condensation risk at the suspended ground floor junctions though the introduction of either type of solid wall insulation removed the condensation risk.

The introduction of EWI, however, worsened the pre-existing condensation risk for the solid ground floor, though insulating the DPC insulation then removed this risk.

The front wall to gable wall junction was a risk of condensation when uninsulated; the introduction of the IWI and EWI at this corner reduced the risks considerably, though did not fully remove this risk. Where TIWI existed on the gable wall, the risk was completely removed; indicating a small amount of IWI return on the EWI wall would be sufficient to remove the risk.

3.4.5 Alternative scenario analysis

Additional thermal bridging analysis was carried out to explore the impact of alternative retrofit scenarios for the suspended floor junction with the gable wall and front wall, with and without insulation. The results are shown in Table 3-9:

Table 3-9 Alternative scenario model results; suspended ground floor to external wall junctions with and without floor insulation (red = risk of condensation).

	Floor	Wall	DPC	Ψ-value W/(m·K)	Heat loss W/K	Temperature factor
EWI (gable)	Un-insulated	Un-insulated	Un-insulated	-0.038	-0.13	0.72
EWI (gable)	Insulated	Un-insulated	Un-insulated	0.087	0.31	0.71
EWI (gable)	Insulated	EWI	Un-insulated	0.435	1.53	0.78
EWI (gable)	Un-insulated	EWI	Un-insulated	0.333	1.18	0.80
EWI (gable)	Insulated	EWI	Insulated	0.360	1.27	0.81
EWI (gable)	Un-insulated	EWI	Insulated	0.247	0.87	0.82
IWI (front wall)	Un-insulated	Un-insulated	n/a	-0.049	-0.28	0.72
IWI (front wall)	Insulated	Un-insulated	n/a	0.038	0.22	0.71
IWI (front wall)	Insulated	IWI	n/a	0.012	0.07	0.83
IWI (front wall)	Un-insulated	IWI	n/a	-0.062	-0.36	0.84

In the uninsulated base case scenario, the floor to wall junction is determined to be at risk of surface condensation, though thermal bridging heat loss is not an issue (negative bridging is shown due to conventions for calculating thermal bridging account for overlapping geometry and does not refer to heat gains).

Installing IWI is shown to marginally reduce heat loss and eliminate condensation risk at the floor junction. Installing EWI marginally increases heat loss but also eliminates condensation risk. i.e. installing either IWI or EWI removes condensation risk from the floor junction in this case study home, and small increases and decreases in bridging heat losses respectively.

Conversely, insulating the floor without installing any SWI, however, resulted in both a minor increase in thermal bridging heat loss and a marginal increase in condensation risk. Therefore, a risk-based approach to retrofit in solid walled homes, that are similar to 56TR, may be to ensure suspended floor insulation takes place after SWI is installed.

The scenarios also consider the impact on the gable wall of introducing a strip of EWI below DPC level. This is shown to further reduce heat loss and condensation risk, though the improvement is negligible. i.e. although insulating the DPC was the lowest risk scenario for EWI, the result indicates that for this house, leaving the DPC uninsulated did not pose a significant moisture risk and thermal bridging heat losses were only marginally reduced.

These results further suggest that, for this case study home, the previous practice of requiring EWI to extend below DPC level by 400 mm [12], which often required insulation to be installed below ground level, adding substantial costs and time to EWI retrofits, may not be necessary.

In these scenarios, the DPC started (and therefore the EWI stopped) at floor level, which is a relatively common detail. Homes with different relative floor and DPC positions, however, could have differing risks around floor insulation and insulating below DPC. Thus, more investigations of different floor types would be needed to understand how applicable results found here are to the UK housing stock.

Thermal bridging heat losses summary

The calculated equivalent y-value in the uninsulated homes was 0.24, higher than the 0.15 RdSAP default y-value. However, more than half of this was due to a very large thermal bridge at the sloping ceiling to flat ceiling junction where there was a discontinuity in the loft insulation.

When this was rectified in the loft retrofit the thermal bridging heat loss (HTC_b) dropped from 50 W/K to 19 W/K, reducing the equivalent y-value to 0.09. RdSAP overestimated pre-retrofit y-value, but it substantially overestimated the y-value for the retrofitted home.

The rest of the retrofit stages had much less impact on HTC_b, though interestingly the suspended timber floor and hybrid SWI retrofits marginally increased HTC_b by 2 W/K each. The whole house approach reduced this back to 21 W/K and a y-value of 0.10.

The retrofits were successful in reducing condensation risks with the 27 junctions being considered a risk pre-retrofit, reduced to only four post-retrofits. The only junction to increase its risk was the door threshold, which is an interesting finding as limited retrofit options are available for door thresholds and there is no approved measure in the Energy Company Obligations.

The suspended floor retrofit marginally increased condensation risks in the suspended timber floor, though this was already a risk pre-retrofit. The wall insulation subsequently removed the risk, even when the EWI did not extend below the DPC. Conversely, EWI increased pre-existing condensation risk at the solid ground floor, until the DPC was later insulated, suggesting that although no major reduction in heat loss was delivered, the below DPC insulation could reduce condensation risks in solid floor junctions.

The hybrid approach of EWI and IWI meant that a potential bridge occurred at the wall corners where the two systems interacted. In this case study there was a pre-existing condensation risk in the uninsulated home and while this risk was reduced, it was not removed entirely. The IWI did however, remove risk from problematic areas such as party walls, windows and partition walls where risks previously existed.

3.5 Measured, calculated, and modelled retrofit performance

The aggregate whole house HTC has been measured using the coheating test and can be disaggregated into the three individual components:

HTC_v (infiltration heat losses) can be estimated by applying the n/20 rule to the blower door test results.

HTC_f (plane element heat losses including repeated thermal bridging) can be approximated by measuring heat flow via HFPs on all elements and summing the area.

HTC_b (non-repeating thermal bridging heat losses) can be calculated by modelling each junction in thermal bridging software; though it is erroneously often assumed to be the remainder once the HTC_v and HTCf are subtracted from the whole house measured HTC.

In theory, the sum of these three heat losses should equate to the HTC measured by the coheating test. However, differences may occur for several reasons:

- The n / 20 rule (Equation 1) is an annual average approximation which may not be appropriate for different building types or for different levels of wind exposure, geography or topography. Thus, the HTC_v can only be an approximation.
- HFP placements may not be representative or comprehensive of whole element heat loss, so the HTCf may be imperfectly estimated.
- Thermal bridging simulations contain simplifications in geometry and use default data on construction material properties, so may not be representative of actual HTCb.
- Systematic uncertainty in the coheating test cannot be perfectly accounted for, e.g. party wall heat exchange, solar gains, and only quasi-steady-state conditions are possible.

In this section these three component parts are summed to calculate the whole house heat loss, and this is compared to the HTC measured by the coheating test, to quantify the gap between these aggregated and disaggregated methods.

Following this, the measured HTC is compared to the different energy models at each retrofit stage, assuming each of the four calibration steps described in Section 2.7 in this report and in more detail in the DEEP Methods 2.01 Report.

3.5.1 Measured HTC; aggregate vs. disaggregated approaches

The measured aggregate HTC from the coheating test and the disaggregated HTC calculated from summing the HTC_v, HTCf and HTCb are presented in Figure 3-25.

Comparing these two approaches to derive the whole house HTC, is often termed 'closing-the-loop' analysis. It is useful in both exploring where heat losses are occurring and as a reference point for the whole house HTC measured by the coheating test.

The HTC_f is derived by multiplying the area (m²) of each fabric element by its measured U-value (W/(m²·K)), the HTC_v is derived using in Equation 1, and the HTC_b is derived using thermal software as described in the previous chapter.

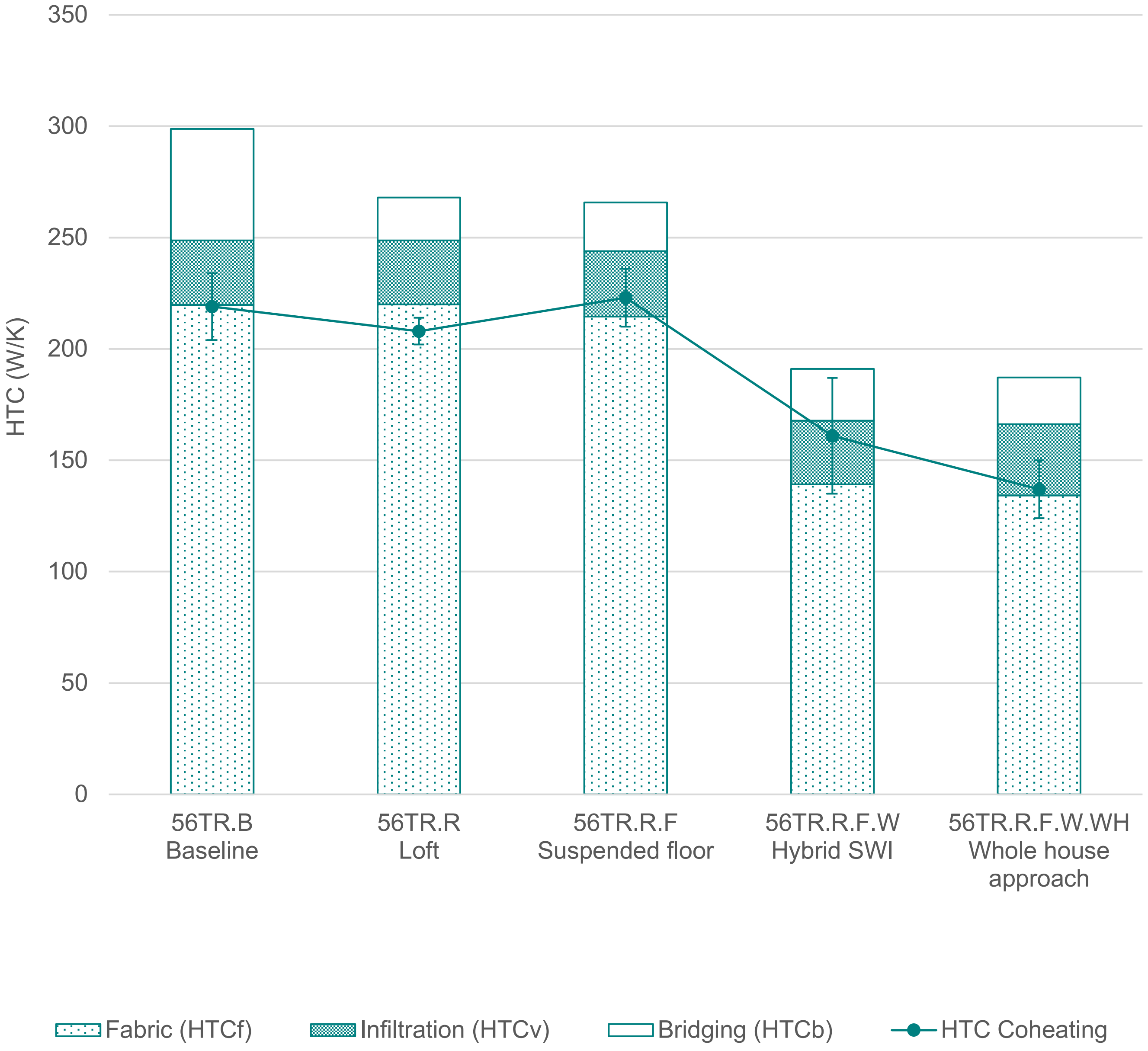


Figure 3-25 Calculated vs measured HTC

The HTC measured by the coheating test is shown to be somewhat different to the sum of the HTC_f, HTC_v and HTC_b. The salient points related to this analysis are discussed below:

- The sum of HTC_f, HTC_v and HTC_b is substantially higher than the coheating HTC in all retrofit stages, and a greater reduction in HTC was predicted by the disaggregated method - 112 W/K compared to the measured value of 82 W/K.

- Reasons for this may be due to uncertainties in the coheating test or in the closing-the-loop disaggregated approach, including:
  - There may be overestimates in the thermal bridging calculations as some assumptions on construction details have been made.
  - The n/20 rule of thumb may be under or over estimating background ventilation heat losses for this type of house.
  - There may also be some uncertainty in the blower door test results, since air exchanges with neighbours may be overestimating HTC_v.
  - Heat flux density plates are not able to capture heterogeneity in heat loss from fabric elements (repeated, or local bridges, or local bypasses), meaning U-values and HTC_f may be overestimated in this house.
  - Point thermal bridges have not been considered.

- A large benefit of the loft retrofit was predicted by the disaggregated method, especially due to a large reduction in HTC_b, though this was not measured in the coheating test.

- A small reduction in HTC_b following the ground floor retrofit was predicted by the disaggregated method, though this was not measured in the coheating test.

- No significant reduction in the whole house approach retrofit was expected according to the disaggregated method since the slight reduction in HTC_f was offset by a marginal increase (within the uncertainty of the test) in air leakage, owing to plaster shrinkage around the edge of the new sloping ceilings.

The proportion of heat lost via fabric, infiltration, and bridging varies according to the retrofit stage, as shown in Table 3-10.

The external walls remain the largest contributor to the HTC despite the significant reduction in heat loss achieved by the IWI and EWI. Heat losses associated with air leakage become increasingly important even though they remain the same size as the rest of the house is retrofitted.

The most significant relative shift in heat loss type is the reduction in non-repeating thermal bridging heat losses after the loft retrofit.

Table 3-10 Whole house heat loss via disaggregated methods

Retrofit stage	HTC_f W/K	HTC_v W/K	HTC_b W/K
56TR.B Base case	220 (74 %)	29 (10 %)	50 (17 %)
56TR.R Loft retrofit	220 (82 %)	29 (11 %)	19 (7 %)
56TR.R.F Suspended timber ground floor insulation	214 (81 %)	29 (11 %)	22 (8 %)
56TR.R.F.W Hybrid IWI & EWI	139 (73 %)	29 (15 %)	23 (12 %)
56TR.R.F.W.WH Whole house approach measures *Sloping roof IWI and below DPC EWI*	134 (72 %)	32 (17 %)	21 (11 %)

The next section discusses how the different modelling software can estimate the HTC reductions from each of the retrofits, and how their predictions can be improved via calibration.

3.5.2 Measured vs. modelled HTC calibration step 1

The measured HTC values for each retrofit stage are plotted against the HTC values predicted by the uncalibrated models using default RdSAP input data in Figure 3-26:

- Steady-state HTC estimates higher HTC compared to the DSM and coheating values for all stages, though the gap reduces after the hybrid IWI & EWI wall retrofit.
- The BREDEM and RdSAP values are very closely aligned, as would be expected, with only small differences in the way that ground floor U-values are calculated and the way that BREDEM accounts for sloping roof areas and chimney volumes.
- DSM predictions of HTC are a remarkably good fit with the measured coheating values and are within the error margin of the test for three out of five stages.
- DSM also predicts the same scale of reduction in HTC that was measured by the external wall retrofit, though not for the other retrofit stages.

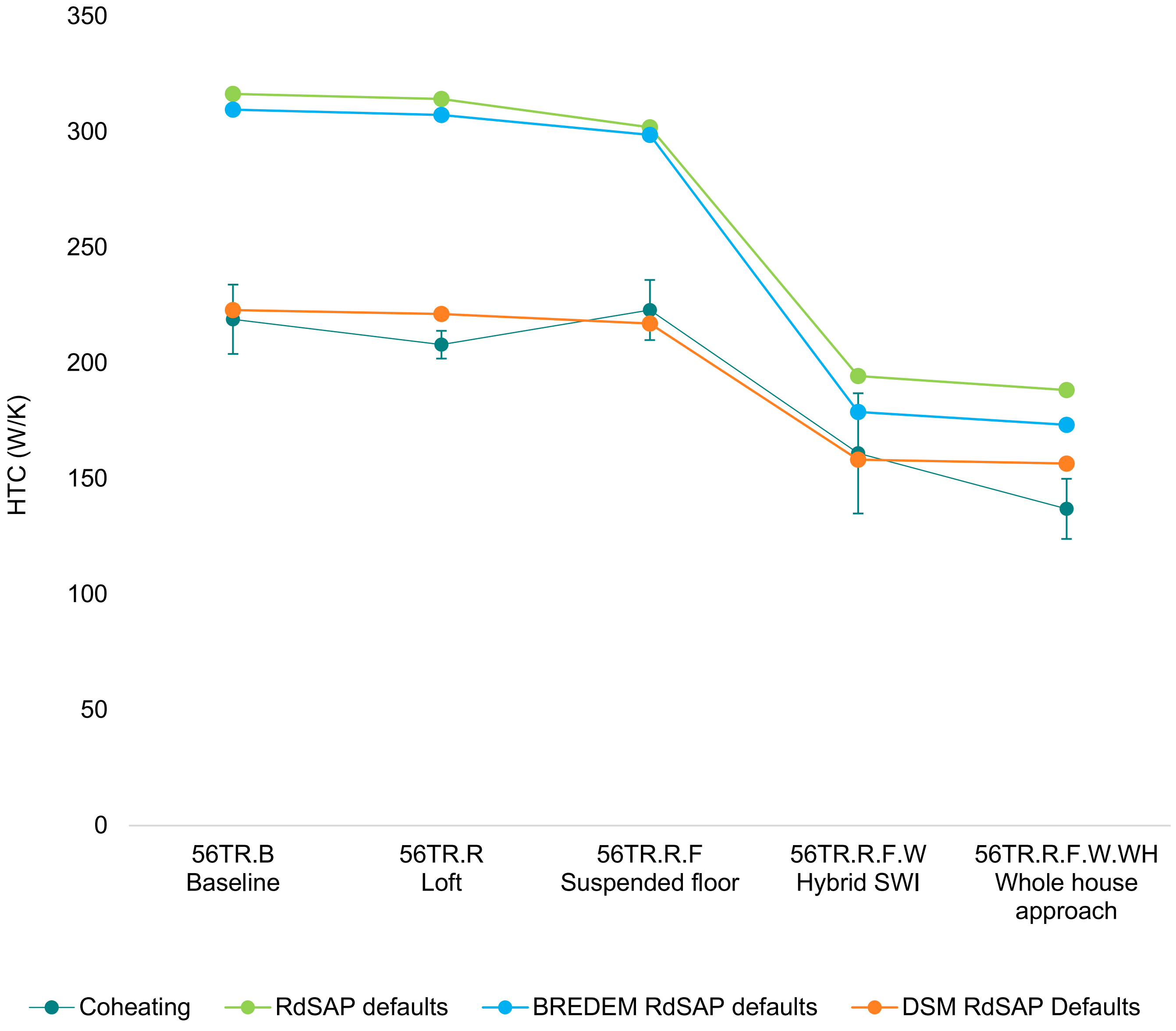


Figure 3-26 Measured vs modelled HTC calibration step 1: default data

3.5.3 Measured vs modelled HTC calibration step 2: measured infiltration

In this first calibration step, the models used infiltration rates derived from the blower door test, as this data is the most likely and most cost-effective measurement data to be acquired in practice. The impact of this compared to the previous calibration stage can be seen in Figure 3-27:

- RdSAP is not included in this calibration step as infiltration cannot be altered in the software, which is a significant limitation.
- There is a marginal reduction in predicted HTC as a result of including the measured air leakage in the models, since these were slightly lower (between 8 and 9 $m^3/(h \cdot m^2)$ @ 50Pa) than the predicted RdSAP default of 10 $m^3/(h \cdot m^2)$ @ 50Pa, though still within the margin of the test error.
- Including measured infiltration data in the models still results in the steady-state models predicting higher HTC values for this case study home than DSM and coheating measurements; by a considerable margin before the SWI is installed.
- The DSM predictions are still in good agreement with the measured values, as the difference between the default and measured infiltration rates are only responsible for a relatively small amount of the overall HTC, between 8 and 11 W/K for BREDEM and DSM respectively.

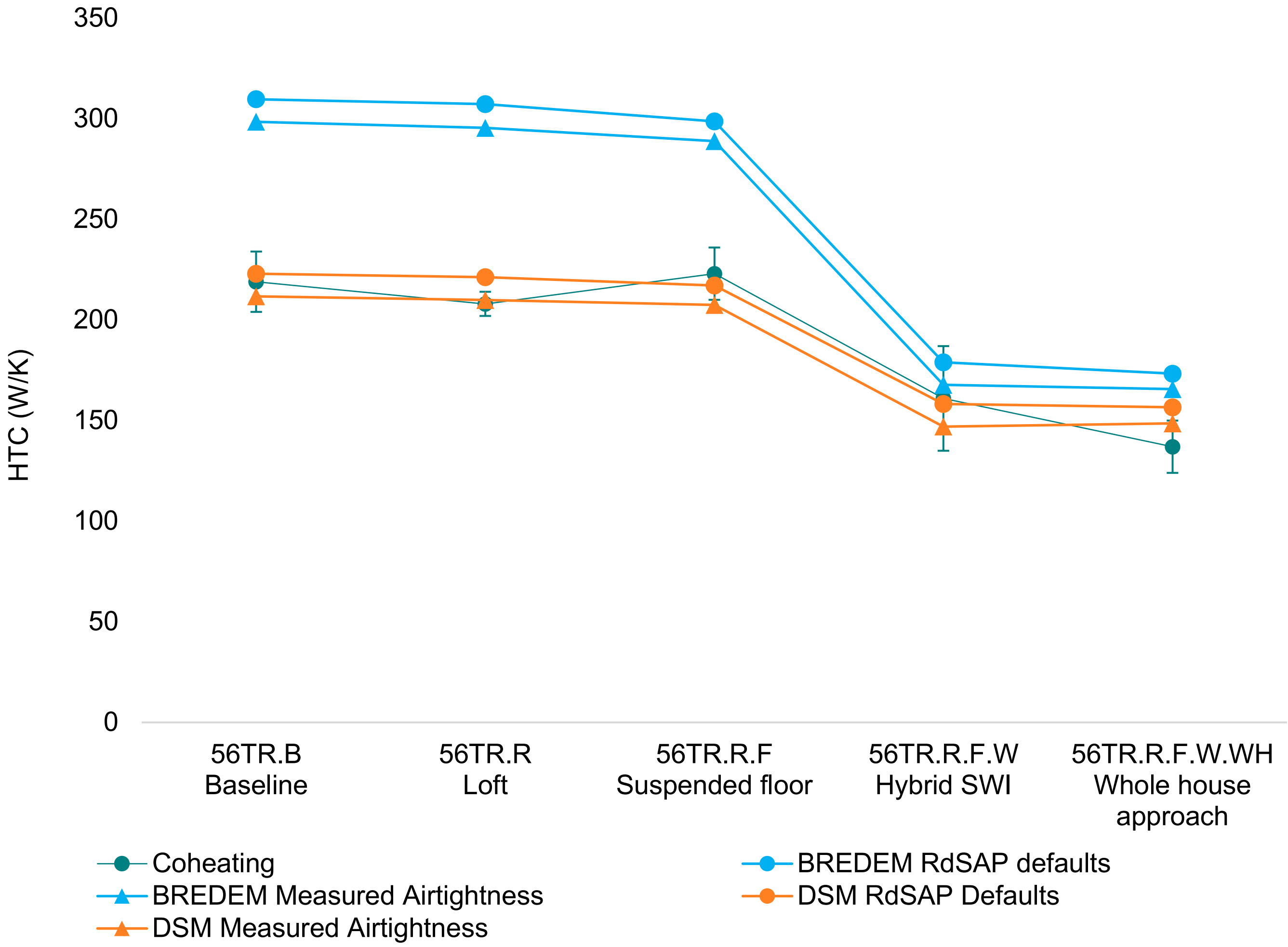


Figure 3-27 Measured vs modelled HTC calibration step 2: measured infiltration

3.5.4 Measured vs modelled HTC calibration step 3: calculated U-values

In this step, the models included U-values defined using the BRE calculator which requires more detailed surveys, often requiring assumptions or destructive investigations to establish the nature and thickness of construction layers. The impact of this compared to the previous calibration stage can be seen in Figure 3-28:

- RdSAP is again not included in this calibration step as only default or measured U-values can be used under the conventions.
- Using calculated U-values makes a marginal difference to the predicted steady-state HTC since the default U-values for the floor, loft and walls were slightly higher than the calculated U-values, while they were lower for the sloping ceiling; thus these changes to some extent cancelled each other out.

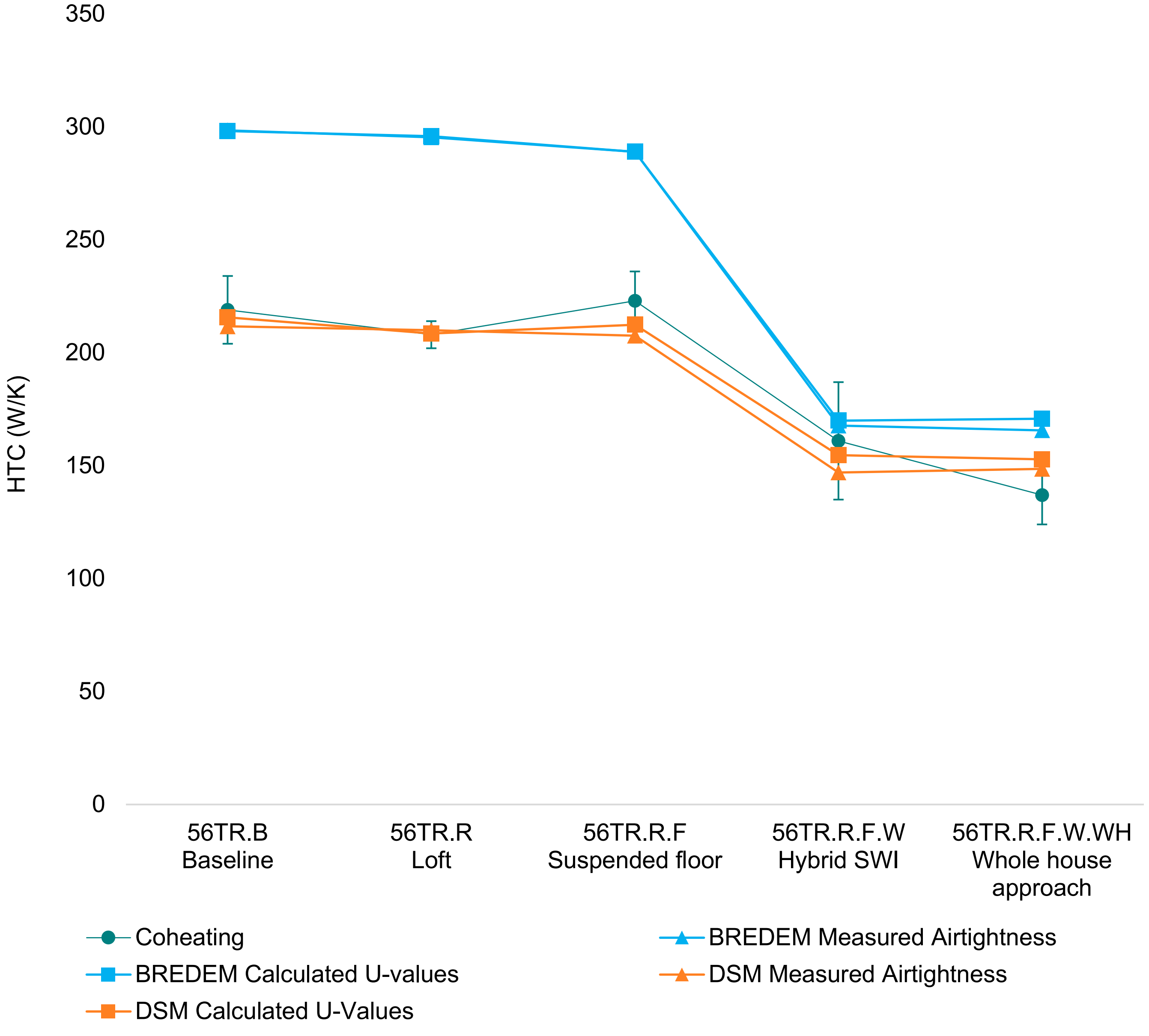


Figure 3-28 Measured vs modelled HTC calibration step 3: calculated U-values

3.5.5 Measured vs modelled HTC calibration step 4: measured U-values

In this step, the models used measured U-values which requires resource intensive in-situ testing. The impact of this compared to the previous calibration stage is shown in Figure 3-29:

- Even when using measured airtightness and U-values, the steady-state models predict higher HTC than the coheating value and DSM model.
- Using measured U-values in steady-state models reduces the HTC predictions for the pre-external wall retrofit models, because the uninsulated external walls had lower measured U-values than the RdSAP defaults and calculated U-values.
- Conversely, the post wall retrofit external wall U-values were measured to be higher than the default and calculated U-values, meaning the post wall retrofit HTC predictions for all the models were further away from the measured values.
- The use of measured U-values does not necessarily make models more aligned with the coheating values. The reason for this is unknown, but it suggests there may be uncertainty in either the way the models calculate heat losses, or in the representativeness of the measured U-values and / or the coheating tests, or may be related the models' assumptions over thermal bridging heat losses.

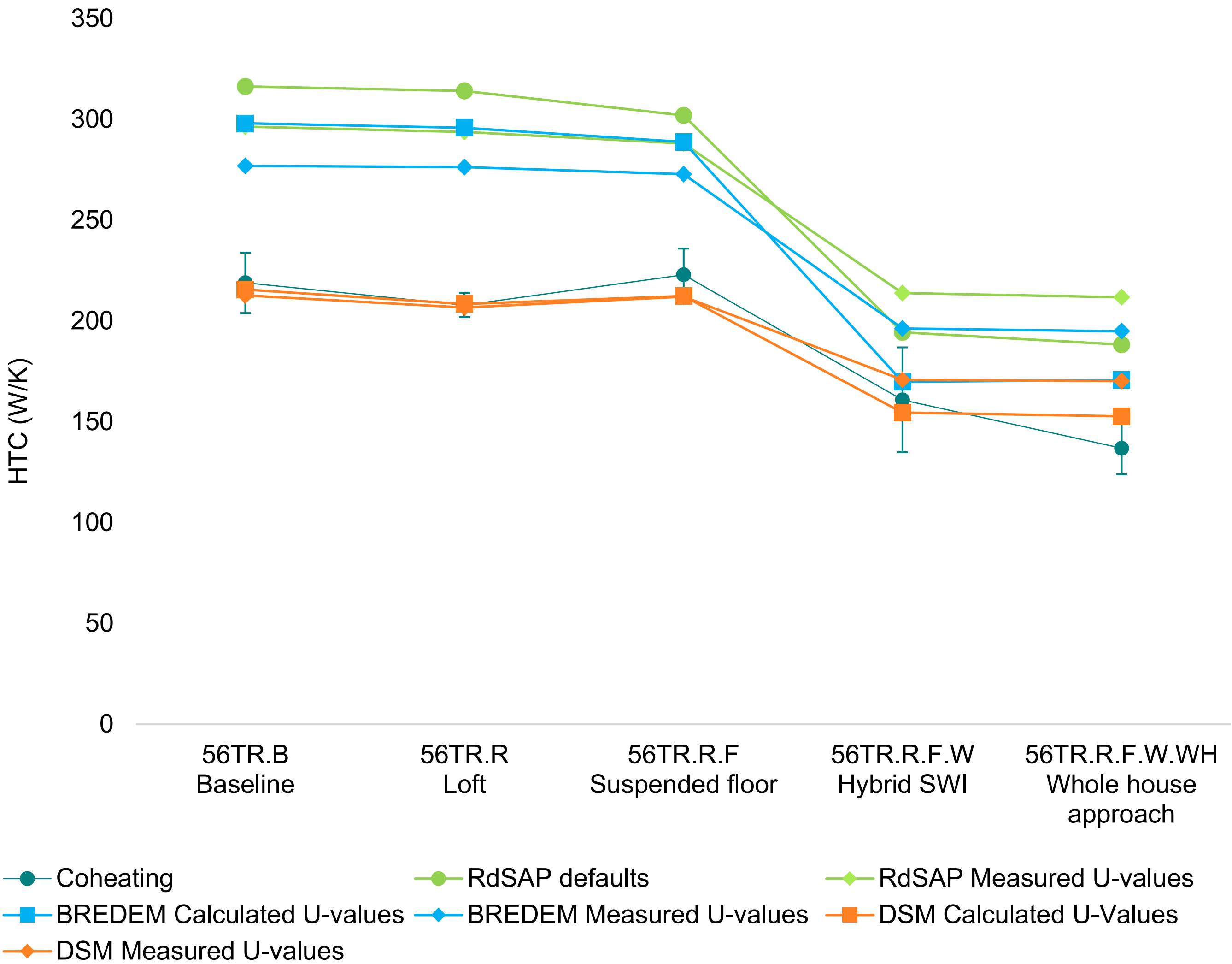


Figure 3-29 Measured vs modelled HTC calibration step 4: measured U-values

3.5.6 Measured vs modelled HTC calibration step 5: calculated thermal bridging

In this step, the models used calculated HTC_b from TRISCO, to update default values, this is a highly specialist and rarely undertaken exercise. The impact of this compared to the previous calibration stage is shown in Figure 3-30:

- RdSAP is not included in this stage as y-values are fixed and cannot be altered. This is a significant limitation.
- In the base case BREDEM model, using the calculated HTC_b increases the overall HTC, indicating that the y-value is too low for the uninsulated home.
- Conversely, when retrofitted, the use of the calculated HTC_b reduces the whole house HTC, suggesting that the y-value is too high for the insulated home.
- However, using calculated non-repeating thermal bridging in DSM reduced the HTC in all stages for this house, indicating that the default values are higher than those used in DSM. This also points to the difference in the way that thermal bridges are allocated in steady-state models compared to DSM, which may require further investigation.
- Including calculated thermal bridging means the benefit of addressing the large thermal bridge in the loft previously described in Section 3.4.2 can be captured. This results in the loft retrofit now reducing overall HTC by 31 W/K in the BREDEM model compared to 1 W/K previously assumed. This improvement in HTC_b is more than a third of the reduction achieved by the external wall retrofits. Similarly, the loft retrofit is now predicted to achieve a 15 W/K saving in DSM when using the calculated thermal bridging, but only 6 W/K when using the defaults, and the HTC predicted by DSM for the fully retrofitted home is now in good agreement with the coheating value.

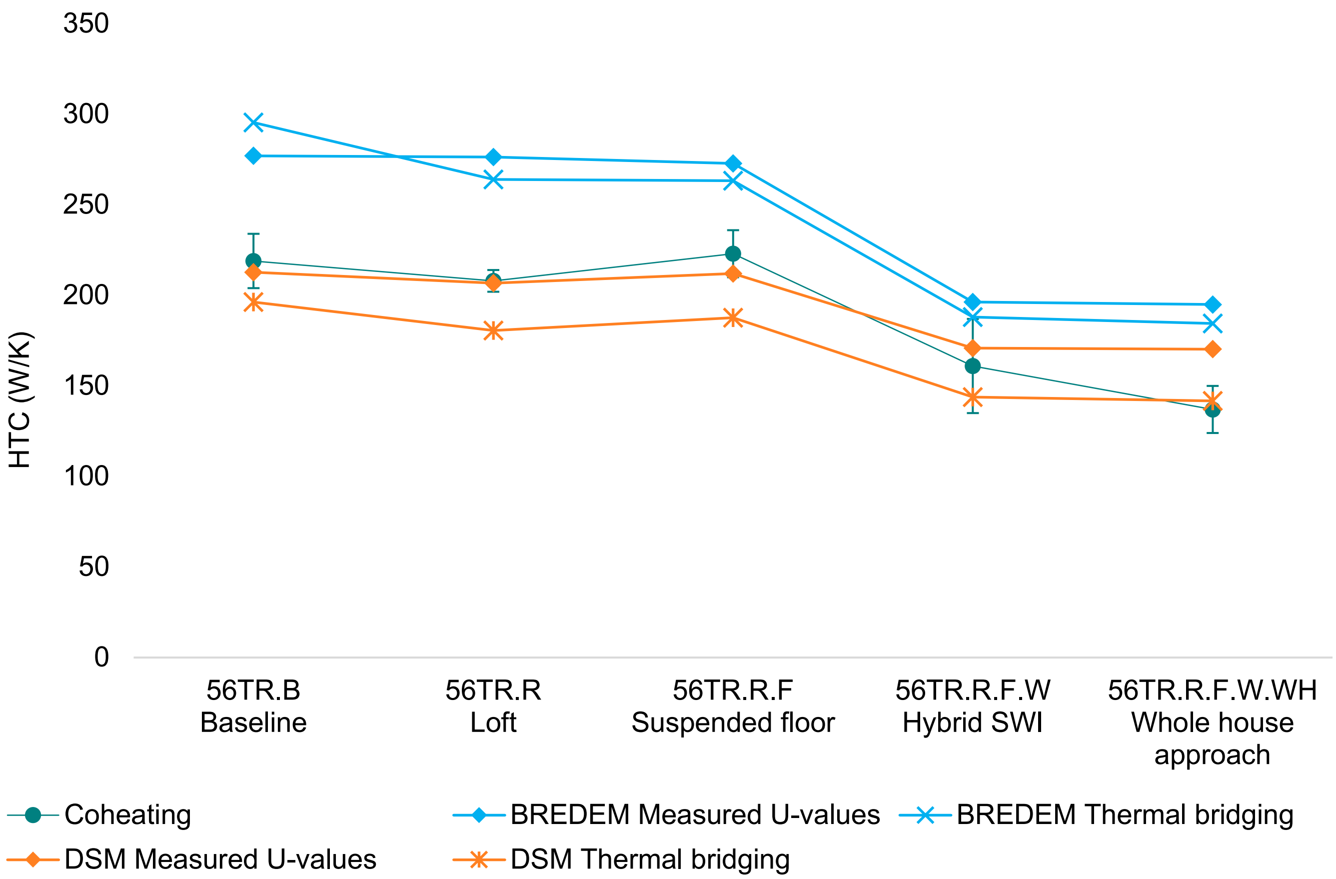


Figure 3-30 Measured vs modelled HTC calibration step 5: calculated thermal bridging

Measured versus modelled HTC summary

The closing-the-loop analysis showed that the disaggregated HTC prediction based on measured U-values, and infiltration and calculated non-repeating thermal bridging heat loss was not only significantly higher that the HTC measured by the coheating test, but it was also beyond the uncertainty limits associated with the coheating test.

This may be due to the U-values, that were recorded, not being representative of the plane elements, and overestimating heat loss. It may also be that the n/20 approximation of air leakage heat losses may not be appropriate for this home. Additionally, the co-pressurisation results suggested that undertaking a conventional blower door test on such a dwelling may be overestimating infiltration, since the post-retrofitted home result may have dropped from 8.99 to 8.64 $m^3/(h \cdot m^2)$ @ 50Pa, though this is within the error of the test.

There was also a discrepancy in the measured coheating HTC compared to the HTC derived from the steady-state models, though this reduced somewhat when the measured infiltration rate,U-values, and calculated non-repeating thermal bridging were included. Also, the prediction became much closer to the measured value when the external walls were insulated and there was less discrepancy in the predicted and measured U-values.

The DSM models predicted a more similar value to that which was measured using the coheating test, at all retrofit stages, even when using default U-values, infiltration rates, and non-repeating thermal bridging values.

After the external wall retrofits, the next largest predicted reduction in HTC achieved was by the reduction in the calculated non-repeating thermal bridging heat loss savings achieved by the loft retrofit. Yet, when using default non-repeating thermal bridging values (y-values in RdSAP and BREDEM) the benefit of re-installing loft insulation is marginal.

The results suggest that one way to increase the accuracy of EPCs would be for assessors to have different non-repeating thermal bridging heat loss defaults to select from, depending on whether different elements are insulated not. In addition, there should also be the ability to insert measured or calculated U-values and measured air infiltration, where this data is available.

3.6 Predicting EPC band, annual space heating, and carbon emissions

EPC bands, space heating requirements, carbon reductions, and fuel bill savings are commonly used for retrofit policy evaluation. DEEP did not perform any longitudinal monitoring of energy consumption pre- and post-retrofit in the case study homes, however, the energy models can predict the impact of the retrofits on these metrics.

To do this, all models shared matching occupancy profiles and internal heat gain inputs as defined in the RdSAP conventions. These are described in detail in the DEEP Methods 2.01 Report. The use of matching occupancy profiles was undertaken to provide a useful comparison between the modelling approaches, based upon changes to fabric inputs only. However, despite having matching assumptions for gains and occupancy, the resulting space heating demand from the RdSAP, BREDEM, and DSM models differed substantially.

Dynamic and steady-state models are fundamentally different, in that DSM calculates heat balances and demand at an hourly timestep, whereas RdSAP and BREDEM calculate these for a typical day of each month and extrapolate results for an annual prediction. Thus, the complex interactions between heat gains and heat demand that take place over a diurnal cycle are only captured in DSM. It is beyond the scope of this project to confirm which approach is more accurate, but it is clear that the RdSAP and BREDEM models consistently predict higher space heating demand than DSM.

This is significant when considering the success of retrofits and calculating paybacks or impacts on EPC levels and fuel poverty for policy evaluation, i.e. RdSAP age band default data were found to underestimate baseline EPC scores, and thus overestimate retrofit savings.

3.6.1 Impact of retrofits on EPC bands

Several policy mechanisms set EPC targets, and the Government have set an ambition that all homes, where practically possible, will achieve an EPC band C by 2035 [13]. The impact of the retrofits on EPC scores in this case study as predicted by each model at each calibration stage is shown in Figure 3-31. The heat demand predicted by DSM is the only output that differs in the comparative EPC calculations.

- Steady-state models generally predict lower EPC bands than DSM, though when the EWI is installed the EPCs for all models are in closer agreement.
- Despite the variation in SAP scores, all models prior to the external wall retrofit award the home an EPC band D, except the DSM model when calculated non-repeating thermal bridging are included.
- All the models award the home an EPC band C when the external walls are insulated and have much closer SAP scores. This confirms the importance of insulating solid external walls if policy targets for homes to achieve EPC band C are to be met.
- No retrofit awards an EPC band B, indicating that it will be challenging for solid external walled homes like 56TR to improve their thermal performance beyond an EPC band C with conventional fabric and air leakage interventions. The EPC Band C is very wide from SAP 69 to SAP 80; policy may benefit from more granular banding: C1, C2, etc.

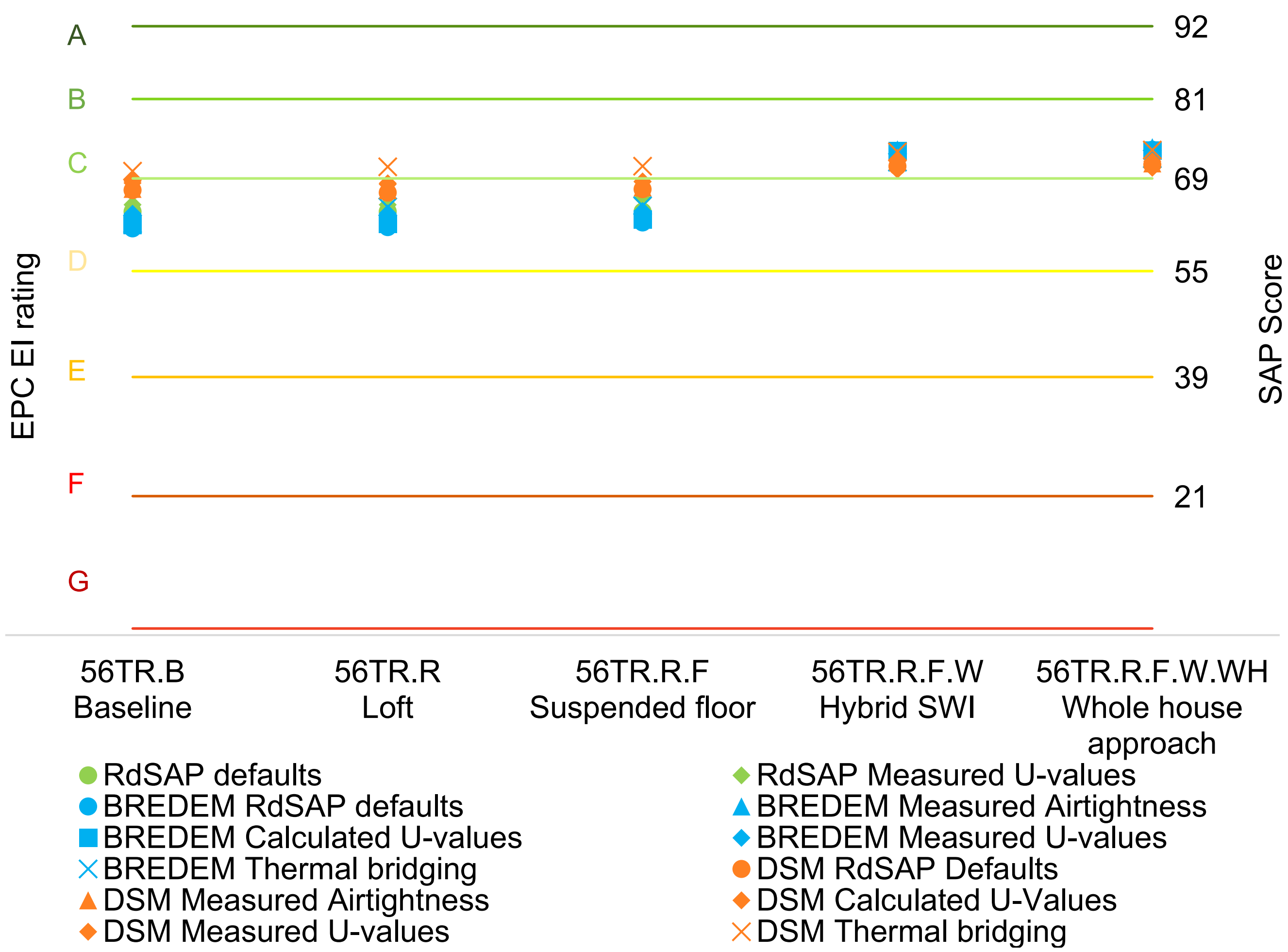


Figure 3-31 Predicted impact of retrofits on EPC band

3.6.2 Impact of retrofits on annual space heating

The Social Housing Decarbonisation Fund (SHDF) Wave 1 evaluates retrofit success by setting an annual space heating target of 90 kWh per m² for retrofits [14]. The predicted annual space heating demand for the case study retrofits is shown in Figure 3-32.

- The combined retrofits bring the annual space heating down to between 78 and 97 kWh per m² depending on the model used, a reduction of between 12 % and 50 %, respectively. This is a very large variation in predicted savings, which has implications for policy or funding that relies on models for cost saving estimates.
- The external wall retrofits are responsible for almost all of this reduction in each of the models, 86 % according to the EPC RdSAP model, or 67 % and 69 % according to the final calibrated BREDEM and DSM models respectively.
- The SHDF 90 kWh per m² target is only met by some models. For steady-state models the target is met in all cases except when measured U-values are included, since these were higher than the defaults. For DSM, no models meet the threshold except in the final stage when calculated thermal bridging is included.
- The variation between the models' predicted annual space heating demand is reduced significantly post external wall retrofit.

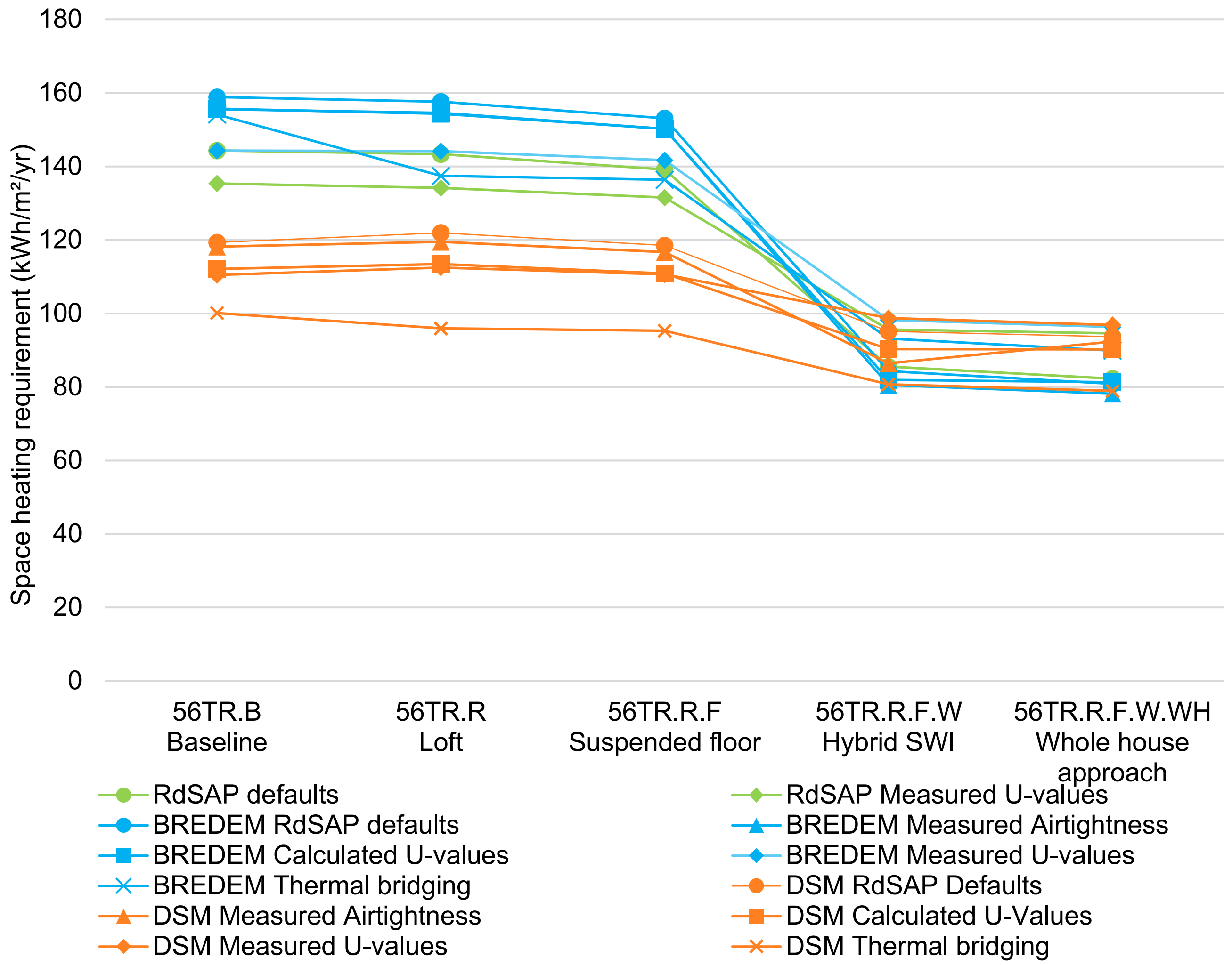


Figure 3-32 Predicted annual space heating demand

3.6.3 Impact of retrofits on CO_2 emissions

Space heating homes is responsible for around 15 % of the UK's CO_2 emissions [15]. 56TR's CO_2 emissions were predicted to be reduced by between 8 % and 36 % depending on which model and inputs were assumed. The savings achieved by each retrofit are shown in Figure 3-33.

- Almost all the reductions in CO_2 emissions are due to the external wall retrofits, indicating that any policy focussed on carbon emission reductions from solid externally walled homes should focus on insulating the external walls.
- The reduction in thermal bridging heat loss in the BREDEM model during the loft retrofit also achieved some CO_2 reductions, which could indicate that some benefits of loft insulation are not being fully captured by existing energy and carbon models that rely on default y-values.
- DSM models tend to predict lower savings and even predict increased CO_2 emission in the loft and whole house retrofit stages due to a marginal increase in measured air leakage. However, these increases are within the error margin of the test method.
- When measured U-values are included, the CO_2 savings are smaller post EWI retrofit since there was a relatively large performance and model prediction gap associated with the external wall insulation.

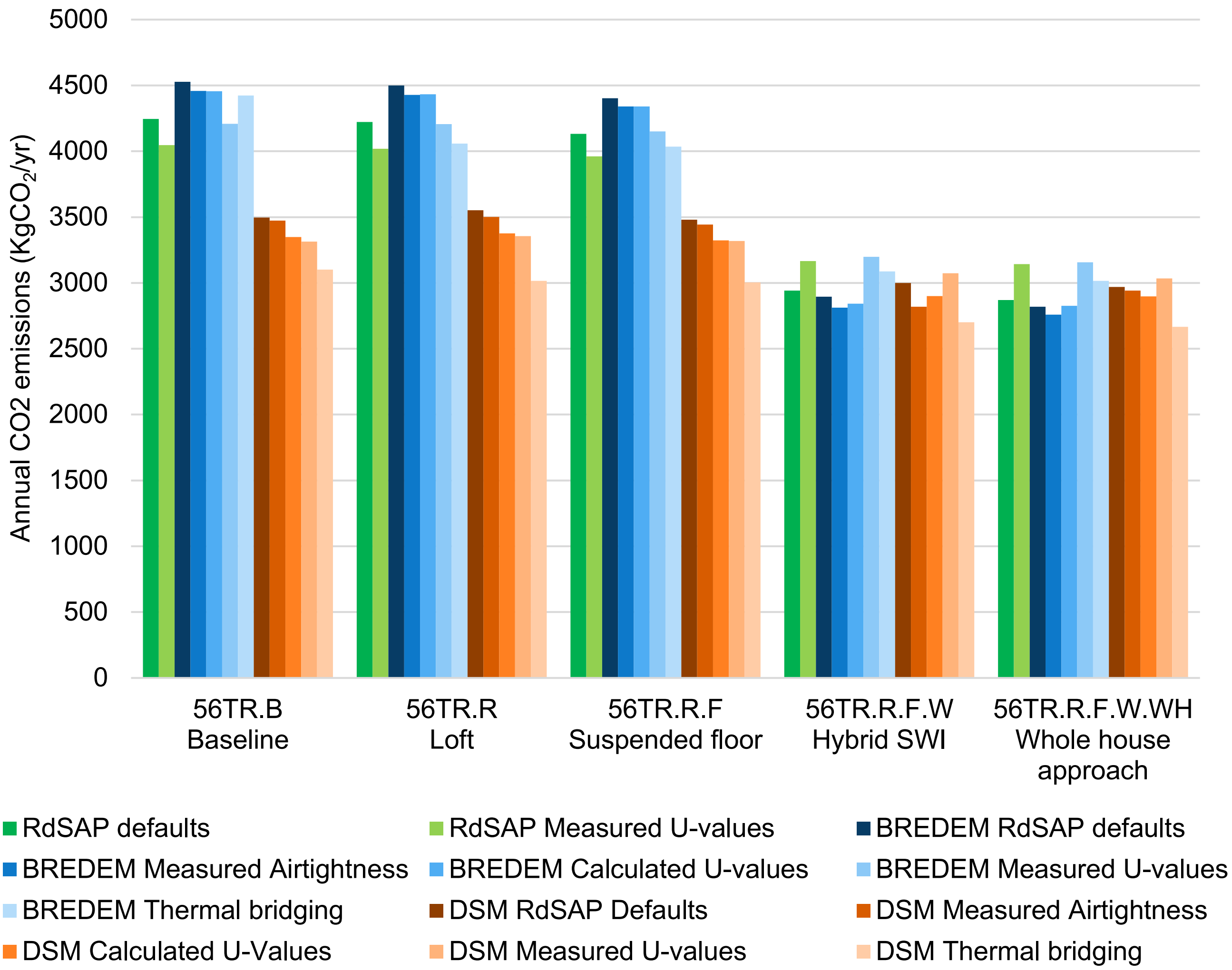


Figure 3-33 Annual CO_2 emission after each individual retrofit

3.6.4 Potential reasons for differences in annual model outputs

Fundamental differences between steady-state and DSM models cause inherent discrepancies in the predicted heat loss and energy calculations for the DEEP case studies. The differences between the models are discussed in the DEEP Methods 2.01 Report, and are summarised here:

Internal heat gains from occupants, lighting and equipment
The total heat gain from each of these sources in DSM is adjusted to closely match that in BREDEM. However, as they are hourly heat balance calculations, there may be periods when useful gains may offset some fuel use as they align with periods of heating.

Heating set points and schedules
These have been adjusted to match those used in BREDEM. However, the hourly resolution of the weather data means that in some instances heating demand can occur in warmer daylight hours within DSM models; equally, some heating may occur during periods of lower temperatures in the morning and evening.

Hourly vs daily average external temperature
The external air temperature used in the hourly heat balance calculations naturally differ from the total daily average.

Solar gain through glazing
BREDEM limits glazing orientation to the cardinal and ordinal directions whereas the dwelling is modelled in its true orientation within DSM. This can lead to differences in internal solar gain, particularly during daylight hours in heat demand periods.

Hourly vs daily average solar irradiance (external surface temperatures)
External surface temperature is an important part of the dynamic hourly heat loss calculations through all plane elements in DSM. Higher external surface temperatures will lead to lower heat loss; this will be more pronounced in dwellings with a greater area of south facing plane elements. The reverse can occur during darker winter months although the thermal mass of the constructions can retain some heat after sundown.

Geometry
DSM models exclude areas and volumes for chimney breasts, partition walls, and intermediate floors in the total heated space. This inherently means a smaller volume of air is conditioned than that used in the RdSAP calculations.

Weather
Due to the temporal resolution and variability of weather, it is not possible to match to the BREDEM inputs in the same way as the internal gains. The weather file used in the DSM was selected due to the close similarities between monthly average external temperature values (CIBSE Test Reference Year file for Leeds [16]) as discussed in the DEEP Methods 2.01 Report.

Differences specific to 56TR
For the 56TR baseline scenario, using measured infiltration rate and U-values, BREDEM predicts a space heating demand that is 5,482 kWh/year higher than DSM. As with all DEEP case studies, it is the HTC value that has the greatest influence on the annual space heating demand estimates. BREDEM (and therefore SAP/RdSAP) uses a bottom-up method to calculate the HTC used in the heat balance calculations, based upon the thermal transmittance and area of constructions, and background infiltration rates. The DSM models mimic the

coheating test conditions and therefore use a top-down method to calculate the HTC. Using an unrestricted version on the BREDEM software, it is possible to overwrite the HTC with that calculated in the DSM model.

Following this adjustment, the normalised annual space heating demand in BREDEM is 7,953 kWh, compared with the DSM estimate of 8,539 kWh, meaning that BREDEM predicts a demand lower by 585 kWh. The BREDEM calculations can be further normalised by using the DSM volume of conditioned space (28.60 m^3 less in the DSM model). Following this final adjustment, the BREDEM estimate is 1,493 kWh lower than the DSM output. In the case of 56TR, BREDEM included solar heat gains of 2,320 kWh and the DSM 2,397 kWh so there is very little difference between the two models. The results of the normalisation exercise suggest that the other differences between the two modelling approaches have a limited impact of space heating demand predictions.

As noted above, solar irradiance can influence the dynamic hourly heat loss calculations included in the DSM. The influence of solar irradiance on external surface temperatures is particularly pronounced in the case of 56TR due to the geometry and orientation of the dwelling. The front of the house faces south-west, and the large, exposed gable wall area faces south-east. Both façades are therefore exposed to solar irradiation for large parts of the day, along with most of the roof.

The DSM visualisations shown in Figure 3-34 illustrate this effect, with data presented for days with a low, medium, and high amount of solar affecting the external surface temperatures. Thermal images of the same façades are presented in Figure 3-35 to illustrates this.

Further work is required to understand the full extent that the differences will have on models across the DEEP portfolio of case study dwellings and a comparison is presented in the summary report. This will also have an influence on the calculated HTCs, but this will be less distinct as the modelled coheating tests are run over the month of February only.

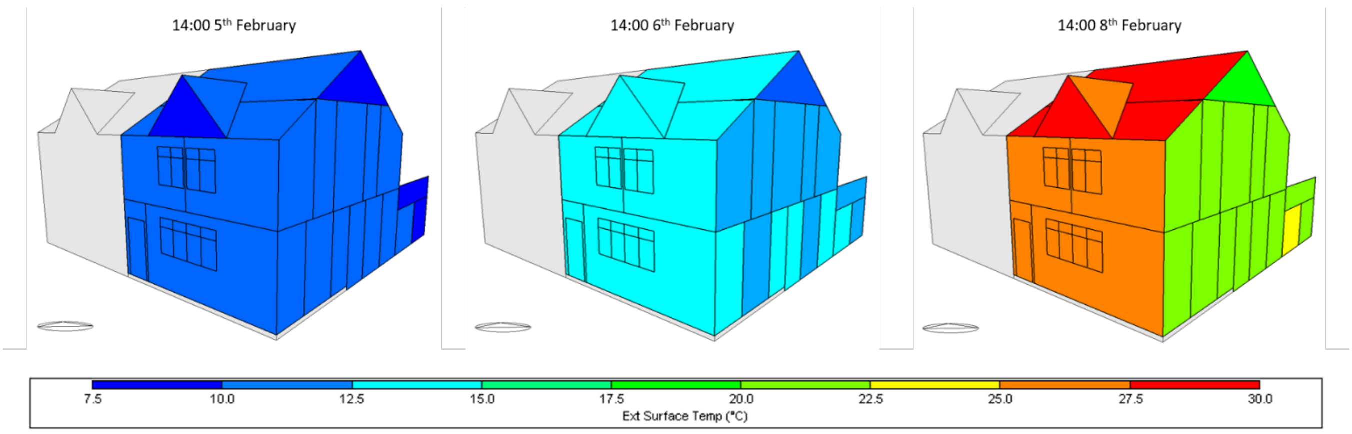


Figure 3-34 External surface temperatures in DSM baseline model

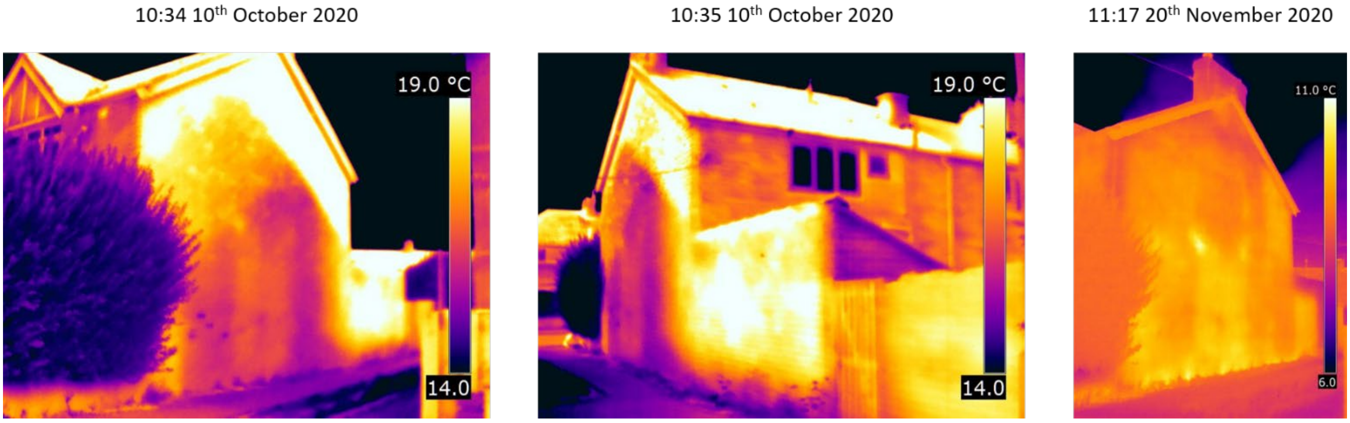


Figure 3-35 External surface temperatures from thermography surveys

Predicting EPC band, space heating, and carbon reductions summary

All the models agreed that the hybrid external wall insulation brought the home into an EPC band C, from its starting point in band D, no matter what default or updated input data were used. None of the other retrofits, however, made any significant improvement to the home's SAP points. This suggests that solid external wall insulation is likely to be the most effective and meaningful approach to achieving the national EPC target of C for solid externally walled homes like 56TR.

Steady-state models also predicted that the hybrid external wall insulation would roughly half the space heating demand in the home, to bring it closer to the SHDF target of 90 kWh/year. The RdSAP model used to generate the EPCs did predict this target would be reached, but not all models agreed on this prediction. Most of the models would have also met this target if there was not a substantial performance gap associated with the external wall insulation.

The retrofits were predicted to reduce CO_2 emissions by between 8 % and 36 %, achieved almost exclusively by the external wall retrofits. The loft and ground floor retrofits were not predicted to have meaningfully contributed. The only notable exception was that some benefit was observed when the calculated non-repeating thermal bridging heat loss was included in the BREDEM model.

In the case of 56TR, direct solar gains through glazing accounted for very little difference between model types. Whilst the BREDEM model using measured inputs predicted a significantly higher annual space heating demand, when normalised using the DSM HTC and volume, the difference between predicted space heating demand was relatively low.

3.7 Overheating risk of retrofitting

As part of the overall DEEP project, Loughborough University carried out parametric analysis of overheating scenarios, using a 10-year weather data file. The overheating analysis in this section is complementary to this work and uses the overheating assessment method from CIBSE TM59, which is cited within the PAS2035 guidance [17].

Two metrics are used to assess whether the dwelling will overheat. The first is taken from another CIBSE publication, TM52: *The limits of thermal comfort: avoiding overheating in European buildings* [18]. The two assessment criteria are defined as follows:

A. For living rooms, kitchens, and bedrooms: the number of hours during which the ΔT (difference between the operative and comfort threshold temperature) is greater than or equal to one degree (K) during the period May to September inclusive, shall not be more than 3 % of occupied hours.

B. For bedrooms only: to guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1 % of annual hours. (Note: 1 % of the annual hours between 22:00 and 07:00 for bedrooms is 32 hours).

Overheating assessment has been carried out at each stage of the retrofit. Following the TM59 guidance, the initial assessment was completed using the CIBSE Design Summer Year 1 (DSY1) file for a 2020s high emission scenario at the 50th percentile, for Leeds in this instance. There are three different DSY files available for the 14 UK regional locations. They use actual year weather data that simulate different heatwave intensities: DSY1 represents a moderately warm summer; DSY2 represents a short, intense warm spell; and DSY3 a longer, less intense warm spell [16]. Assessment was also carried out for future weather scenarios, using the DSY1 files for the 2050s and 2080s high emission scenarios at the 50th percentile. As with all naturally ventilated homes, it is the percentage of openable area in the windows that has the strongest influence on overheating risk; these are illustrated in Figure 3-36.

Figure 3-36 Percentage of opening area for openable windows

Results for Criteria A are shown in Figure 337. In the base case home under current climate conditions, all rooms except the kitchen and dining room (both with north-east facing windows), are at risk of overheating throughout the day. This risk in inevitably more pronounced in the future climate scenarios. It is worth noting however, that overheating risk in the kitchen and dining room spaces reduces to below the Criteria A threshold in all climate scenarios once the whole house retrofit stage is completed. Overheating increases marginally after both the roof and floor retrofit stages but begins to reduce once the wall insulation is introduced.

The final whole house stage reduces overheating to the extent that the kitchen and dining room do not exceed the threshold even in the 2080s climate scenario. The retrofit at this stage includes insulation of the rear utility space and insulating the sloped skeiling elements on the first floor, which limit heat transfer sufficiently to significantly reduce overheating risk in the bedroom spaces. The implications of this suggest that by only partially insulating homes, thereby still allowing some uninsulated areas of fabric to act as a route for solar radiation to enter dwellings, may mean that the retrofit does not reduce the risk of overheating. Thus, to reduce overheating risks, all fabric elements may need to be insulated to limit solar gains entering the home. This supports the notion that a whole house approach to retrofits may be less likely to cause overheating.

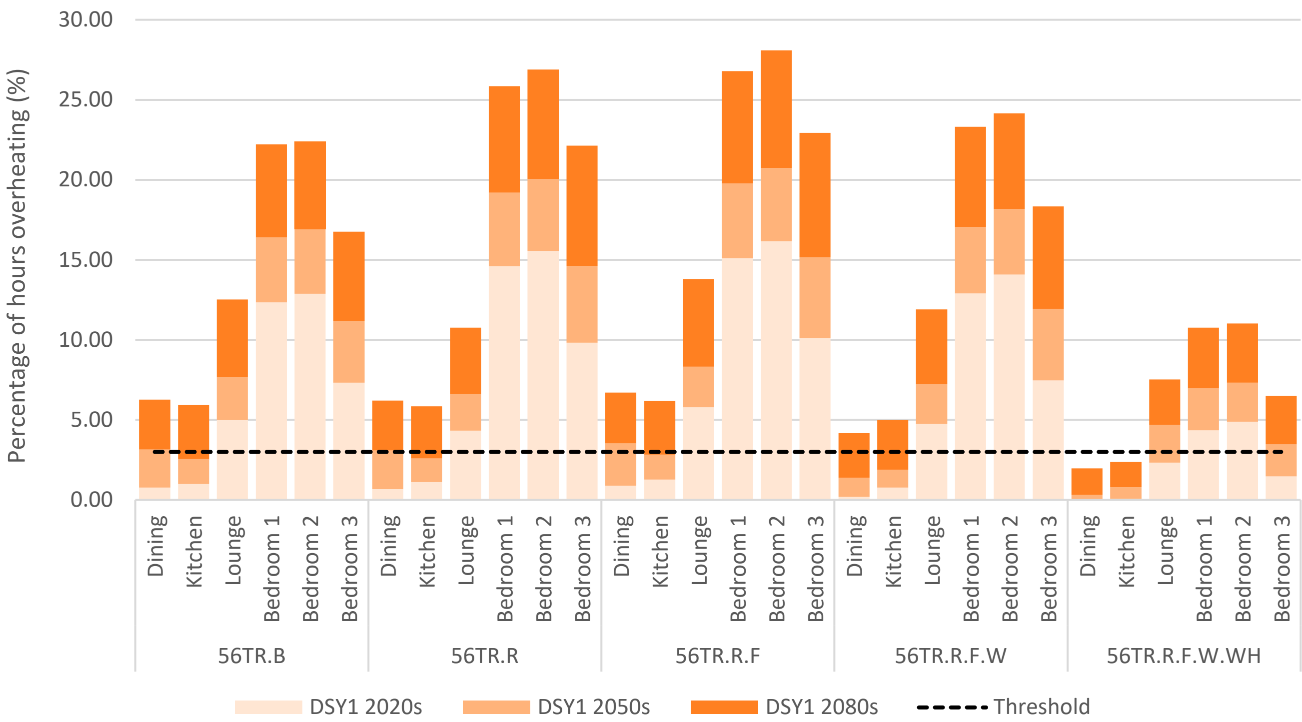


Figure 3-37 Modelled overheating under TM59 Criteria A

Results for the assessment under Criteria B are illustrated in Figure 3-38. As with other DEEP case studies, warmer future climate scenarios result in more cases of overheating in all rooms tested. This is especially the case following the loft and then floor insulation retrofits. The TM59 methodology mandates that bedroom doors are closed overnight so less heat escapes through the ceiling element overnight. This implies that in some partial retrofit scenarios, improving the building fabric, while not limiting solar gains, can increase overheating risks in this type of dwelling.

The same pattern as observed for Criteria A is observed for Criteria B, with the whole house approach to retrofit resulting in the lowest risk, but also the ground floor insulation substantially reducing overheating frequency. It is not until solar heat transfer is reduced through the solid walls and skeiling elements that the number of hours considered to overheat begins to reduce. It is important to note, however, that in all cases the bedrooms exceed the Criteria B threshold. As noted above, bedroom doors are closed overnight in the TM59 assessment, and it is this, coupled with relatively small window opening areas, that leads to the bedrooms overheating.

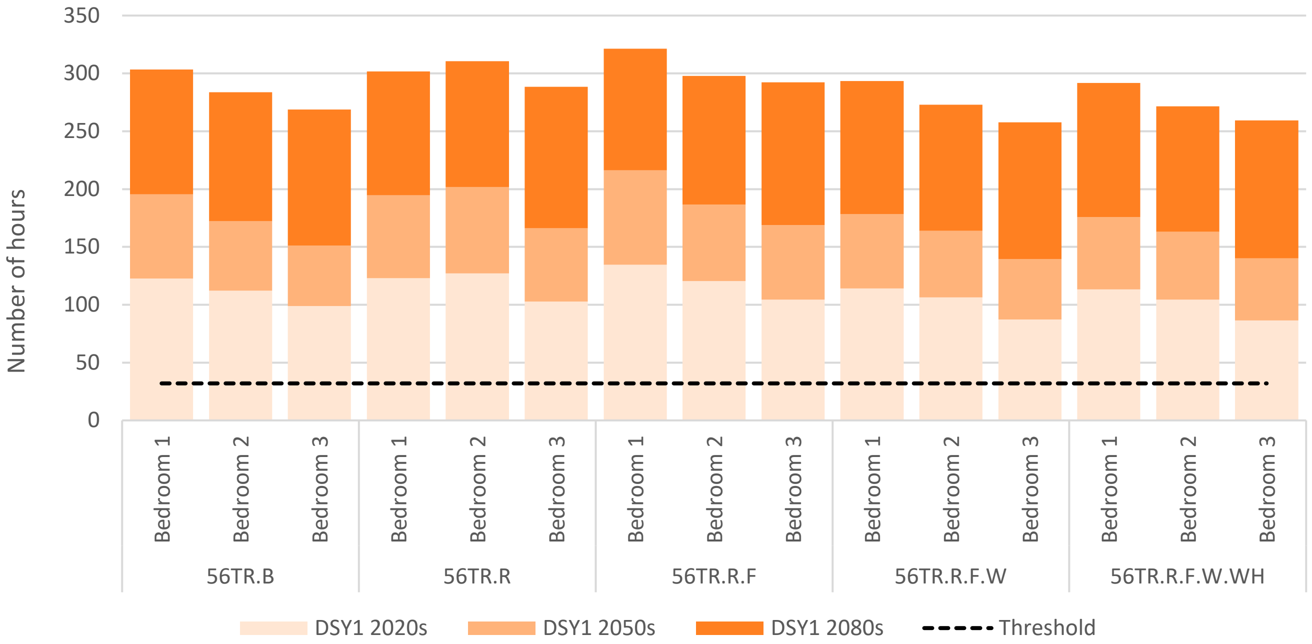


Figure 3-38 Modelled overheating under TM59 Criteria B

Overheating risk of retrofit summary

The uninsulated dwelling is anticipated to substantially overheat, and this will be exacerbated in future climates.

The loft and ground floor retrofits increased the overheating risk, but external wall insulation and insulation in the occupied pitched roof (skeiling element) helped to reduce risk, especially during the day when internal doors aid air movement throughout the entire dwelling.

The results imply that improving some fabric elements, while still allowing solar radiation to transfer heat into the building through opaque elements (via the sloping ceiling and walls), are likely to increase overheating, even beyond that observed in the uninsulated home; this is intuitive as both elements directly couple solar irradiation to the occupied spaces.

Therefore, a whole house approach to retrofit may be the lowest risk option to reduce overheating, though even when this is employed, overheating may still occur in the home. This suggests additional mitigation strategies to limit undesirable heat being generated or entering the home may still be needed.

3.8 Retrofit surface condensation risks

To measure the risk of surface condensation before and after the retrofits, surface temperature measurements were undertaken at locations within 56TR, at sites where non-repeating thermal bridges and discontinuities of insulation were expected to pose a risk. Surface temperature measurements were targeted at junctions where the EWI and IWI meet and where they meet other elements.

T-type thermocouple temperature sensors were placed on the building fabric and monitored during the coheating periods, from the base case stage onwards (See the DEEP 2.01 Report, section 2.7 for methods). The quasi-steady-state conditions of the coheating test provided comparably steady conditions for comparison with numerical thermal simulation. The sensors were removed after the external wall retrofit and whole house retrofit to allow building works and subsequently replaced as close to the original positions as possible.

Temperature factors were used to indicate whether a location is at risk of surface condensation. A temperature factor below the critical temperature factor of 0.75 is considered to be at risk for a dwelling. The temperature factor (f_{Rsi}) is calculated using Equation 2, see section 3.4.4 for the full equation.

Temperature factors are usually used in conjunction with steady-state simulations. In this study, to validate the stability of temperature factors calculated, the averaging method in BS ISO 9869: 2014 was adopted. Where a surface temperature location was unable to satisfy the validation steps, it was considered to have failed.

The risk of condensation occurring does not mean condensation will necessarily manifest; risk may be mitigated by ensuring adequate ventilation in the dwelling generally, but also ensuring air circulation behind furniture and, as this project identifies, behind built-in units located on external walls. Conditions at each location are discussed in the following sections.

3.8.1 Gable wall junctions

Surface temperature sensors were fitted to four junctions between the gable wall and other elements, including the front and rear external walls, sloped ceiling, and the intermediate floor. Temperature factors were then calculated at each junction for each retrofit stage. Locations for measurements are shown in Figure 3-39 and Figure 3-40esults of the calculations as well as comparisons to temperature factors calculated from thermal simulations are included in Table 3-11, values below 0.75, which indicate that the junction is at risk of condensation, are highlighted in red.

Figure 3-39 Photographs and IR images of gable wall showing position of surface temperature sensors Top: 1 and 2. Bottom: 3

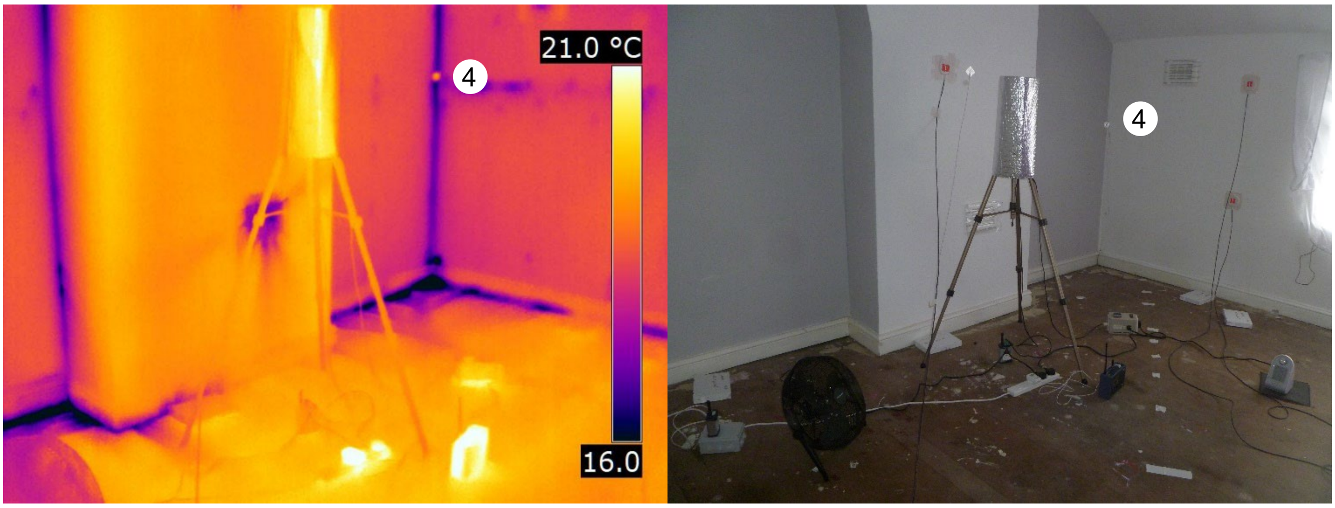


Figure 3-40 Thermal and visual image of surface temperature 4 location at front wall to gable wall junction

As shown in Table 3-11, measured temperature factors were lower than simulated temperature factors, prior to external wall insulation. Consequently, all junctions with the gable wall were at risk of condensation. After the installation of external wall insulation, temperature factors increased at all junctions. However, at the junction between the gable wall and the rear external wall, as well as the sloped ceiling, the temperature factor remained below 0.75. This was due to the thermal bridge that exists between the EWI on the gable wall and the IWI installed on the rear external wall and the sloped ceiling.

Table 3-11 Comparison of temperature factors calculated from measurements and thermal simulations at gable wall junctions

Retrofit stage		Gable junction f_{Rsi}			
		Rear wall (1)	Sloped ceiling (2)	Int. floor (3)	Front wall (4)
Pre-retrofit	Measured	0.61 (±0.09)	0.62 (±0.09)	0.70 (±0.06)	0.73 (±0.08)
	Simulated	0.61	0.66	0.72	0.78
Loft	Measured	0.63 (±0.04)	0.65 (±0.04)	0.74 (±0.03)	0.75 (± 0.04)
	Simulated	0.61	0.66	0.72	0.78
Floor	Measured	0.60 (±0.06)	0.65 (±0.05)	0.71 (±0.03)	0.70 (±0.08)
	Simulated	0.61	0.66	0.72	0.78
Wall insulation	Measured	0.71 (±0.11)	0.72 (±0.09)	0.95 (±0.02)	0.84 (±0.05)
	Simulated	0.74	0.71	0.95	0.81
Whole house	Measured	0.69 (±0.06)	0.72 (±0.07)	0.89 (±0.04)	0.86 (±0.10)
	Simulated	0.74	0.71	0.95	0.81

The junction between the gable wall and the front external wall and the intermediate floor experienced a greater increase in temperature factor due to the continuous insulation layer. The EWI on the gable wall is continuous over the intermediate floor junction, and the gable wall at the external wall junction was fitted with a thin layer of IWI left over from the base case, which created an uninterrupted insulation layer.

3.8.2 Front and rear external wall junctions

Surface temperature sensors were fitted to four junctions between the front and rear external walls and other elements, including the eaves to the sloped ceiling, the intermediate floor, and partition walls. Temperature factors were then calculated at each junction for each retrofit stage. Locations for measurements are shown in Figure 3-41.

Figure 3-41 Photographs and IR images of rear wall showing position of surface temperature sensors. Top: 1 and 2. Bottom: 3

Results of the calculations, as well as comparisons to temperature factors calculated from thermal simulations, are included in Table 3-12. Values below 0.75, which indicate that the junction is at risk of condensation, are highlighted in red.

Table 3-12 Comparison of temperature factors calculated from measurements and thermal simulations at front and rear external wall junctions

Stage		Front/ rear wall f_{Rsi}				
		Rear eaves (1)	Rear-int. floor (2)	Bedroom-partition (3)	Bathroom-partition (4)	Front-partition (5)
Pre-retrofit	Measured	0.77 (±0.04)	0.68 (±0.08)	0.75 (±0.07)	0.69 (±0.09)	0.84 (±0.08)
	Simulated	0.76	0.73	0.74	0.74	0.74
Loft	Measured	0.77 (±0.03)	0.73 (±0.07)	0.78 (±0.03)	0.67 (±0.05)	0.77 (±0.04)
	Simulated	0.76	0.73	0.74	0.74	0.74
Floor	Measured	0.77 (±0.03)	0.67 (±0.05)	0.76 (±0.04)	0.69 (±0.08)	0.81 (±0.08)
	Simulated	0.76	0.73	0.74	0.74	0.74
Wall insulation	Measured	0.84 (±0.04)	0.91 (±0.04)	0.89 (±0.04)	0.89 (±0.03)	0.93 (±0.05)
	Simulated	0.88	0.87	0.80	0.80	0.80
Whole house	Measured	0.82 (±0.02)	0.83 (±0.04)	0.90 (±0.02)	0.88 (±0.03)	0.89 (±0.10)
	Simulated	0.88	0.87	0.80	0.80	0.80

Table 3-12 above shows that the rear external wall to eaves and partition wall on the bedroom side were not at risk of condensation in the base case. The intermediate floor junctions and the partition wall on the bathroom side were both assessed to be at risk of condensation.

The introduction of IWI during the external wall insulation retrofit stage led to an increase in temperature factor at all the front and rear external wall junctions measured, eliminating the risk at the junctions that were previously below the 0.75 critical temperature factor. This is due to the IWI installed on the front and rear external walls forming a continuous layer of insulation, and at the partition junctions the thickness of insulation installed was sufficient to lengthen the heat loss path, and thus increase the surface temperature at the junction.

In contrast with the gable wall junctions discussed in the previous section (3.8.1) where insulation retrofits were able to reduce but not fully eliminate surface condensation risks at each junction, condensation risk at each front and rear external wall junction measured was fully eliminated. This difference is due to the use of matching IWI on both sides of the front and rear external wall junctions reducing thermal bridging. At the gable wall junctions, the dissimilar EWI on the gable wall and IWI on the front and rear external walls and sloped ceilings led to a discontinuity of the insulation layer and a thermal bypass leading to greater thermal bridging and surface condensation risk. At the front wall to gable wall junction this thermal discontinuity was not a problem due to the IWI on the internal face of the external wall that was left in place from the base case.

Retrofit risks summary

Installing insulation whilst ensuring continuity of the insulation layer resulted in reduced surface condensation risk at junctions compared to discontinuous or uninsulated junctions. However, risks were not eliminated at all junctions, particularly where dissimilar insulation retrofits met.

Junctions where dissimilar insulation retrofits met were at greater risk of condensation than junctions with a single continuous insulation layer. Junctions between external walls fitted with EWI and elements fitted with other insulation systems can also be at risk due to the presence of a thermal bypass between the disconnected insulation layers.

The presence of additional insulation to remedy the discontinuity between dissimilar insulation systems results in a further increase in temperature factor, removing moisture risk at the junction. Additional IWI returns and EWI installed below DPC level are effective at eliminating the surface condensation risk.

3.9 Retrofit costs and payback

This section looks at the costs of undertaking the retrofit described in this case study. However, as only a single case study, these should not be used to generalise costs of retrofits nationally. Undertaking work in existing homes can have tremendously variable costs, depending on the specification of the work being undertaken, as well as the condition of the house prior to retrofit.

Cost data presented here may not be representative for the national retrofit market. Since retrofit tends to be labour intensive, there are variations across the country based on regional differences in construction labour markets. The data discussed here originates from a single contractor in the North of England and relates to only one house type and a limited range of retrofit specifications.

Decoration costs were excluded from the costs reported here since the landlords were undertaking their own Decent Homes repairs following the retrofits and would take on some of the decoration work. However, costs associated with decorating were outside the scope of this project; these have been found to represent around 14 % of the cost of IWI [19], though may be different for EWI, loft insulation, ground floor insulation, and new windows and doors.

The costs of the 56TR retrofits are outlined in Table 3-13 and Table 3-14. The total whole house retrofit cost was £ 59,074, with around three quarters of the costs associated with the hybrid wall insulation retrofit. It is important to note the doors and windows were not replaced as they had been recently replaced.

Activities that took place that were not directly associated with the retrofit itself are termed ‘enabling’ costs in the tables and refer to any kind of necessary remedial or ancillary activity before or after the works took place. In 56TR, there was large amount of enabling costs associated with the loft retrofit, since this involved removing the existing insulation that was present. This may not normally take place.

Similarly, the hybrid external wall retrofit had very high enabling costs (a third of the total costs) that made it much more expensive than the benchmark costs, though it is possible these costs may also be incurred on other retrofit projects.

Another reason the hybrid external wall insulation was higher than the benchmark estimates is that the IWI and EWI systems chosen by the landlord were relatively novel: wood fibre IWI and steel frame and blown wool EWI solutions respectively, which were much more expensive than alternative products.

The landlord opted for breathable and non-foam materials since they associated these with decreased damp and fire risks.

In addition, installing retrofits in piecemeal order in a single home rather than installing all the retrofits in one go in multiple homes also increases retrofit costs due to:

- multiple waste removal costs for each piecemeal retrofit
- reduced staff downtime if workers can work on other jobs while waiting
- requirement to ‘make good’ after each piecemeal retrofit
- reductions in total overhead costs for a single project duration
- economies of scale associated with undertaking work in more than one dwelling

The suspended timber ground floor insulation costs were in line with benchmark expectations even though the ground floor needed removal.

Table 3-13 Costs of retrofits

Retrofit	Retrofit activity	Retrofit costs	Additional enabling work required	Enabling work costs
56TR.R Loft replacement	Install new 420 mm mineral wool between and over rafters including in eaves	£ 1,900	Removal of existing debris and insulation	£ 350
56TR.R.F Suspended ground floor	Lift floorboards and replace with Insulate between joists Replace skirting	£ 2,000	New floor needed Disposal of old floorboards	£ 1,100
56TR.R.F.W Hybrid IWI & EWI	Install wood fibre insulation to internal face of front and rear walls Replace skirting and replaster walls Scan of gable wall and installation of EWI Insulation blower hire	£ 29,636	Extra scaffold, materials and skip New facia boards including insulation Repoint chimney and roof ridge Remove and replace kitchen & bathroom units & extract fans Plumbing repairs Remedial activities to EWI pointing	£ 14,358
56TR.R.F.W.WH Whole house approach	Remove sloping ceiling Install new insulated sloping ceiling Replaster ceilings Install EWI below DPC	£ 9,479	IWI re plastering	£ 250

Table 3-14 explores how the costs of the retrofits relates to the savings that were achieved. As can be seen, overall, the whole house retrofit cost around £ 580 to £ 950, per W/K reduction in HTC. This is relatively high, since neither the ground floor nor the whole house approach retrofits achieved statistically significant savings according to the coheating test. The following section discusses how the retrofits affect annual fuel bills.

Table 3-14 Assessment of cost of retrofit

Retrofit	Direct retrofit	Enabling	Total cost	Proportion of whole house retrofit costs	Cost / element area	Benchmark (£/m²) [20]	Cost per W/K reduction
56TR.R	84 %	16 %	£ 2,250	4 %	£ 76	£ 10 - £ 20	£ 132 - £ 450
56TR.R.F	65 %	35 %	£ 3,100	5 %	£ 66	£ 38 - £ 92	-
56TR.R.F.W	67 %	33 %	£ 43,994	74 %	£ 438	£ 55 - £ 148	£ 475 - £ 1,313
56TR.R.F.W.WH	97 %	3 %	£ 9,729	16 %	£ 509		-

Combined	**73 %**	**27 %**	**£ 59,073**				**£ 580 - £ 950**

3.9.1 Predicted fuel bill savings

The impact of the retrofits on household dual fuel bills is shown using the SAP fuel prices of 3p per kWh gas and 13p per kWh electricity. These values are therefore substantially out of date at the writing of this report. The indicative annual fuel bill savings are, however, shown in Figure 3-42 for context.

The only phase that made any significant savings is the hybrid external wall retrofit, which saved between 6 % and 28 % of annual fuel bills. This compares to a national study, which found an average of 18 % reduction in real fuel bills across 940 properties retrofit with solid wall external insulation [21].

DSM predicts substantially lower fuel bills mainly due to variations in heat gain assumptions and ground floor areas and shows the uncertainty that exists surrounding predicting fuel bills using energy models and the type of input data used. This means that predicted annual dual fuel bill reductions for the house vary substantially depending on which model is used, and by potentially more than the savings of the entire whole house retrofit predicted by the model.

The whole house improvements (sloping roof and DPC insulation) which were designed to reduce condensation risks are not expected to yield substantial fuel bill savings. Resolving the discontinuity in the loft insulation however, which would be part of a whole house approach to retrofit, did achieve a reduction of around 2 % to 7 %, though this would not be captured in the predictions unless the thermal bridging calculations were performed.

The airtightness of the home worsened after the whole house retrofit and this is considered without the benefit of the thermal bridging reductions negative savings being shown. Increased levels of air leakage also offset any savings achieved by the loft insulation.

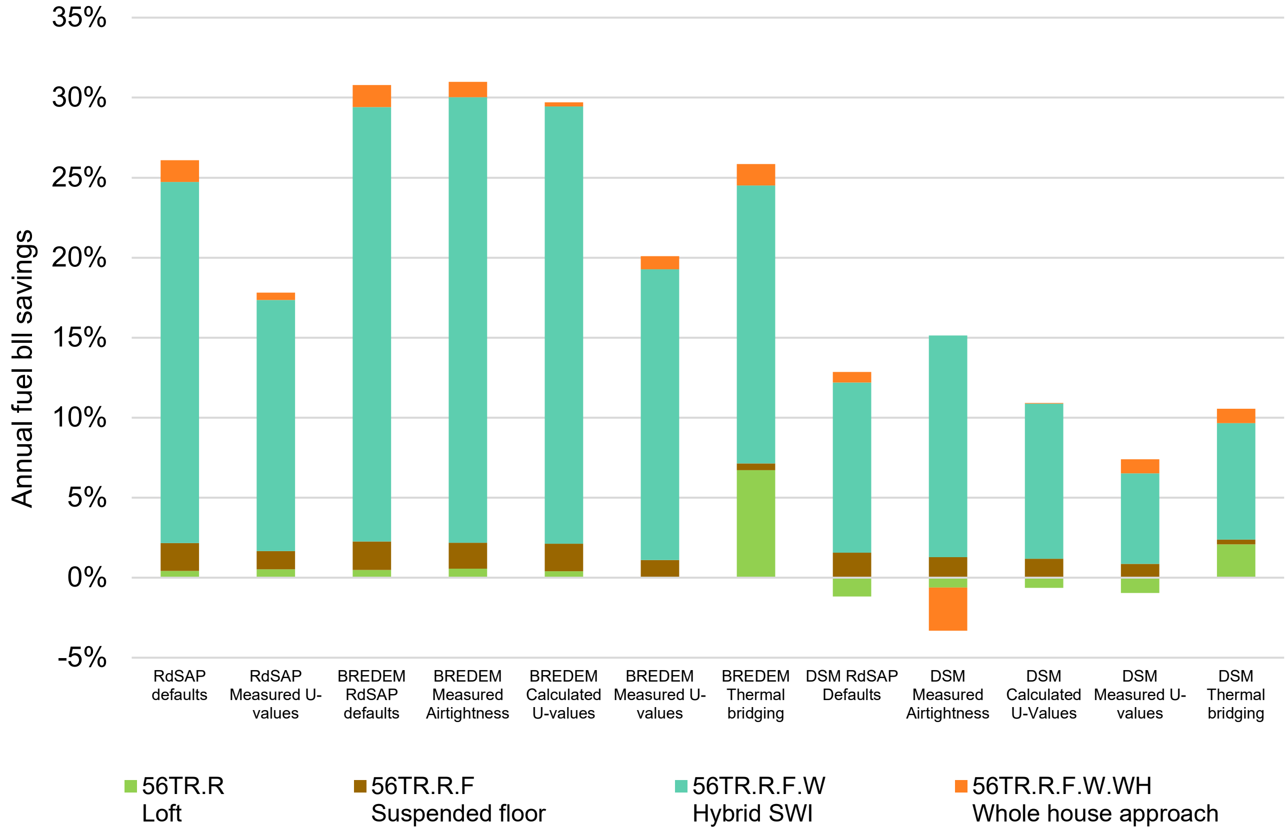


Figure 3-42 Predicted annual fuel bill savings achieved by the retrofits

3.9.2 Predicting simple payback of retrofits

The simple financial payback time, (i.e. not considering fuel price inflation or discount rates) calculated from the retrofit costs and annual fuel bill saving estimates for this case study are shown in Figure 3-43. A logarithmic scale has been used for clarity. Recent fuel and retrofit price increases will significantly affect payback rates and so the values are shown only for illustration, and based on the SAP 2012 fuel price assumptions. The results indicate the following:

- Payback rates vary enormously depending on which model and input data are used.
- The high installation costs associated with the external wall insulation have increased the payback rates to an unattractive level, even though this was the most effective retrofit at reducing heat loss.
- The uninsulated home had some TIWI which also lengthened the external wall insulation payback rates.
- Very high payback rates for the other retrofits are in part due to the models predicting very low heat loss savings.

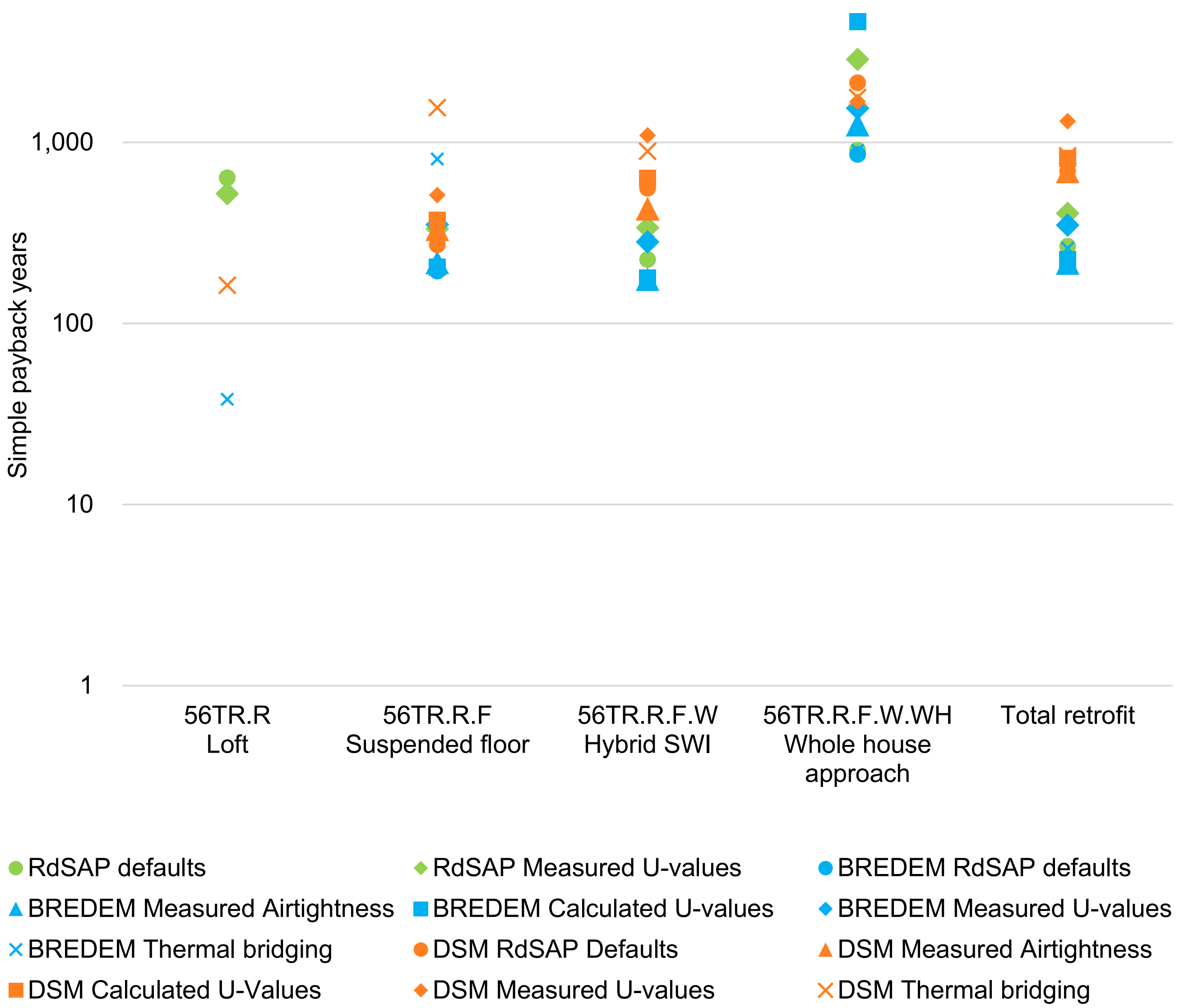


Figure 3-43 Simple retrofit paybacks[14]

Retrofit costs summary

The retrofit costs in this case study were substantially higher than they may normally be, in part owing to it being a non-standard retrofit installation: a high degree of repairs and remedial activity were needed, and so no economies of scale etc. could be achieved; but also because there were many additional repairs demanded by the landlord before and after the retrofit. This is important to consider in retrofit policy since the underlying condition of the home tends to be unknown before work commences.

The cost of undertaking the additional activities to insulate the DPC and sloping ceiling were particularly high. These retrofits resulted in very low predicted fuel bill savings. However, the thermal bridging assessments showed that these retrofits reduced the risk of surface condensation in these locations and failing to reduce surface condensation risk can lead to mould growth and thence to more remedial work. This information is useful in

[14] Some whole house approach retrofits paybacks exceed the 1000 years scale shown in Figure 3-43

informing the balance between cost and risks that need to be considered when retrofitting homes.

The payback rates are therefore relatively unrepresentative of a standard retrofit, and as discussed, the fuel bill savings shown are only provided for illustration as they are based on price assumptions in SAP 2012, which were out of date at the time of publication of this report.

4 Conclusions

This case study has identified important findings about the performance and risks associated with retrofitting solid walled homes, as well as investigating the models used to predict performance and risk. The main issues are discussed below:

Loft insulation
The case study home already had a relatively well insulated loft and in a retrofit assessment it may not have been an area identified for improvement by a retrofit assessor. This project therefore provides information on the potential heat loss reduction improvement that could be achieved by replacing 270 mm of old loft insulation with 420 mm of new insulation to explore if loft top-ups may be a useful retrofit measure.

The results were mixed, with just a (26 ± 2) % reduction in U-values, resulting in only a few W/K predicted HTC reduction in the models.. However, the coheating test recorded a much larger (11 ± 6) W/K reduction, which on closer inspection, was due to the reduction in thermal bridging heat losses that were associated with installing insulation behind the large purlins in the loft (which were previously uninsulated). Doing this ensured that the insulation layer from the loft could be continued to the sloping roof, thus minimising any thermal bridge.

The thermal bridging calculations undertaken predicted that this could have reduced the HTC by 31 W/K (14 %). This indicates there is a discrepancy in the calculations or coheating test accuracy. However, both results are indicative of a measurable benefit that was achieved by replacing the loft insulation, that was not possible to capture in the models. The implication is that using default non-repeating thermal bridging heat loss values can substantially under or overestimate the impact of non-repeating thermal bridging on heat loss and the resulting heat loss savings.

y-values
The default RdSAP y-value of 0.15 was slightly lower than the 0.18 calculated for the baseline home. However, post-retrofit the home's y-value was calculated to be 0.07, half that of the default, owing to the removal of a large thermal bridge in the ceiling. This means the EPC is overpredicting thermal bridging heat losses for homes like 56TR, and so these defaults may benefit from revisions to consider, for instance, the existing insulation installed in homes.

Suspended timber ground floor insulation
This case study home had a part solid, and part suspended timber ground floor, which is a relatively common design in the existing UK housing stock. Thus, this research provides an indication of how much benefit can be achieved from insulating suspended floors when it represents only a fraction (33 %) of the total ground floor and total heat loss area (8 %).

The U-value reduction of (0.22 ± 0.02) W/K (61 ± 4) % achieved by the retrofit was predicted to result in a modest 1 to 12 W/K HTC reduction by the models. These savings were offset completely in some instances by a marginal increase in infiltration between the two retrofit stages (even though the increase was small and within the error of the blower door test), and a slight 3 W/K increase in the amount of non-repeating thermal bridging heat loss at the ground floor to external wall junction, as a result of the retrofit. These increases in heat loss also meant that the coheating test did not show an improvement, predicting a (15 ± 14) W/K increase in HTC.

These findings suggests that there may be negligible heat loss reduction from insulating suspended timber floors in homes, where these represent only a small proportion of the ground floor and total dwelling heat loss area, and where air leakage through the ground floor is either not a significant infiltration issue or is not meaningfully addressed. However, the project did not investigate the benefit of potentially warmer ground floor temperatures, which could provide some thermal benefit to occupants, plus it was found that the addition of the insulation had a positive impact in reducing the risk of overheating.

Hybrid IWI and EWI

There are several situations where homes may have employed a combination or IWI and EWI, for instance where there are planning or heritage restrictions that exclude EWI from a home's front elevation, to protect streetscapes, but do permit EWI on rear elevations.

In this case study the large gable external wall, free of any fenestrations, was ideally suited to the EWI, while IWI was selected for the front and back elevations to maintain the streetscape. Thus, the project comments on the relative performance of the systems and any complications at the interface of the systems at the external wall corners.

The external wall retrofit analysis was somewhat complicated by the presence of TIWI on some, but not all, of the external walls in the pre-retrofit home, which reduced their baseline U-values as low as (1.14 ± 0.14) W/(m²·K). Additionally, the uninsulated external wall U-values were also observed to be varied (between (1.10 ± 0.13) W/(m²·K) and (1.63 ± 0.14) W/(m²·K)), though were generally lower than RdSAP defaults (1.7 W/(m²·K)). The reason for the variability could not be confirmed without destructive investigations, though it may be due to finger cavities in the solid brick wall, which have been observed previously [22], adding additional thermal resistance, though these may also be acting as a thermal bypass. The findings confirm that there can be substantial variability in the heat loss through external solid walls, though the scale and extent of heterogeneous heat flows in UK housing stock is unknown.

The (0.48 ± 0.08) W/(m²·K) U-value achieved by the EWI, however, is not as low as the 0.3 W/(m²·K) predicted value. Additionally, where the gable wall had TIWI, the starting wall U-value was measured to be higher than predicted, which meant that the EWI performed better than predicted. However, for the majority of the external wall, there was no original TIWI meaning the starting U-value was higher than predicted, suggesting a performance gap for the EWI. Despite this, overall, the EWI significantly improved the external wall U-values.

The IWI was designed to reduce external wall U-values to only 0.55 W/(m²·K) (less than the EWI) in accordance with the product manufacturers recommendations to minimise the chances of interstitial condensation and water accumulation. This was measured to be more or less achieved at some locations, but not others, with post-retrofit U-values ranging from (0.58 ± 0.03) W/(m²·K) to (0.82 ± 0.33) W/(m²·K), i.e. between a 26 % and 61 % reduction. Since the starting U-values were lower than they were predicted to be, this means there was also a relatively large, predicted performance gap with the IWI, but again the insulation still substantially reduced heat loss from the external wall.

Cumulatively, the hybrid SWI was measured to achieve a (62 ± 29.5) W/K reduction in HTC (28 ± 13) %, which is around 75 % of the total observed reduction. This may not be a surprise given the external wall represents almost half the heat loss area, and the ground floor and loft retrofits made only marginal impact on the HTC. The SWI alone was adequate to bring the house from an EPC band D to the target C, suggesting that SWI is the most important measure for achieving energy efficiency policy targets for homes like 56TR.

The SWI did not materially affect the non-repeating thermal bridging heat loses that were calculated either, suggesting only a 1 W/K increase post-retrofit. The hybrid EWI and IWI solution leaves a potential bridge at the wall corners where the insulation may not overlap, though this does notcause any condensation risk. Good practice is to overlap EWI and IWI by 400 mm, and indeed the results suggest the absence of a return in this case study resulted in a temperature factor of 0.74 being calculated for the wall corner, which is marginally below the critical threshold of 0.75. However, the findings also suggest this may only provide a negligible heat loss saving.

Damp Proof Course EWI

The modelled reduction in non-repeating thermal bridging heat loss of insulating below DPC level was less than 2 W/K. However, only the gable wall had EWI fitted, half of which joined a solid ground floor, and the other half was a suspended timber ground floor. Thus, the savings may be higher in homes where EWI is installed on all external walls.

The SWI without the DPC added was still adequate at removing the pre-existing condensation risk for the insulated, suspended timber ground floor. Interestingly it did not remove the risk from the adjacent solid floors. The DPC insulation was needed to remove this risk. This means that the DPC EWI may not be a necessary part of a risk-based approach to retrofit where suspended ground floors are already insulated (though they may further reduce the risk) but may be necessary for uninsulated solid floors. More investigation is needed to explore how the DPC insulation affects risks in insulated and uninsulated floor types.

Sloping roof insulation

A relatively common feature in UK homes is to have a ‘skeiling’ or area of sloped ceiling below the loft. This is a problematic area, being neither a loft nor a wall and so being excluded from conventional loft and wall insulation. The consequence of this is that skeilings are generally left uninsulated, causing a thermal bridge, which may be responsible for excess heat losses in winter, excessive solar gains in the summer, and potentially posing a condensation risk in homes. The case study dwelling had such a feature and calculations confirmed that the condensation risk at this uninsulated skeiling was expected to be above the critical temperature factor threshold, especially after IWI had been installed.

The whole house approach retrofit stage saw wood-fibre board installed on the skeiling to reduce the baseline U-value from (0.56 ± 0.02) W/(m²·K) to (0.42 ± 0.06) W/(m²·K). While this reduction was only marginal, owing to the lack of space available to fit insulation without reducing head room, this was judged to be adequate to remove the condensation risk.

Models predicted HTC reductions of up to 3 % from insulation of the sloping ceiling, while the coheating test results suggest that this measure, in combination with the damp proof course EWI resulted in a (23 ± 29.2) W/K (15 ± 18) % reduction in HTC, though this is not significant. The addition of the insulation may have also added an additional leakage pathway into the dwelling (at the unsealed join with the flat ceiling), which may have potentially resulted in some thermal bypassing. The large uncertainty on the result is primarily the result of lack of solar data during the preceding hybrid SWI retrofit stage, meaning the coheating test could not confirm the savings achieved.

If headroom were not a concern, it may have been possible to install more insulation on the skeiling and a larger saving may have been achieved. In this case study, the sloping ceilings were particularly large, (10 % of the heat loss area), thus, HTC reductions in other homes with skeilings may be relatively smaller, unless better U-values were achieved.

Airtightness
Neither the loft, floor, nor external wall retrofits materially affected the airtightness in the home. After the sloping ceilings were replaced, the new plastering cracked at junctions with existing finishes, marginally increasing the air leakage, though it was within the error margin of the test. The house was already measured to be relatively airtight, however, the co-pressurisation tests suggested that 16 % of the infiltration recorded by the blower door test was actually air exchange with the neighbour. This means the blower door test results were overestimating heat loss associated with air leakage, as well as underestimating the amount of fresh air entering a building.

Finally, the Pulse tests predicted more air leakage than the blower door tests, suggesting they also overestimate air leakage, or a different conversion factor may be needed for existing buildings.

Steady-state and dynamic energy models
In this home, as with most other DEEP case studies, the steady-state models substantially overestimated heat loss, when compared to the coheating test. Updating the input assumptions around U-values and airtightness did improve the closeness of the steady-state models to the measured values. Including the calculated non-repeating thermal bridging heat losses also made a substantial improvement, though the final calibrated model still overpredicted heat losses.

As in other DEEP cases studies, the gap between modelled and measured HTC was larger for the uninsulated home since, when insulated, the default U-values more closely matched the measured values.

The DSM models undertaken for this home aligned remarkably well with the measured values, even when default values were used. This was not always the case in other DEEP case studies. Adding measured U-values and infiltration rates made little difference to the accuracy though the non-repeating thermal bridging values resulted in the DSM underpredicting the HTC somewhat. It is not known if the closeness of the DSM and measured values is due to the model accurately reflecting the heat losses observed, or if it was the result of chance.

Predicted overheating risk
The study shows that uninsulated solid external walled homes are at risk of overheating, and that insulating the external walls may increase the number of hours which the home overheats. There is a suggestion that limiting undesirable summertime heat transfer via the ground floor may reduce overheating risk, however this is not well understood.

A whole house approach to retrofit that ensured there was no discontinuities in the fabric insulation, thereby limiting excessive solar gains, was the most successful approach, though this would not be enough to remove the overheating risk. This suggests that alternative measures should be adopted to limit the generation of heat and heat entering the dwelling.

References

1. HM Government, *Table CTSOP4.0: Number of properties by Council Tax band, property build period and region, county and local authority district as at 31 March 2020*, Department of Business Energy and Industrial Strategy, Editor. 2020, Crown Copyright: London.
2. HM Government, *Table CTSOP3.0: Number of properties by Council Tax band, property type and region, county and local*, Department of Business Energy and Industrial Strategy, Editor. 2020, Crown Copyright: London.
3. BSI, *ISO 9869-1:2014 Thermal Insulation - Building Elements - In-Situ Measurement Of Thermal Resistance And Thermal Transmittance - Part 1: Heat Flow Meter Method*. 2014, British Standards Institute: London.
4. DesignBuilder Software Ltd, *DesignBuilder Version 7.0.0.088*. 2021, DesignBuilder Software Ltd,: Stroud, UK.
5. Glew, D., et al., *Demonstration of Energy Efficiency Potential, Literature review of benefits and risks in, domestic retrofit practice and modelling, BEIS Research Paper Number 2021/014*, Department of Busness Energy and Industrial Strategy, Editor. 2021, HM Government, Crown Copyright: London.
6. HM Government, *Approved Document L - Conservation of fuel and power Volume 1: dwellings, Consultation version – January 2021.* 2021.
7. CIBSE, *TM23 Testing buildings for air leakage (2022)*. 2022, CIBSE.
8. BRE, *Solid wall heat losses and the potential for energy saving; Consequences for consideration to maximise SWI benefits: A route-map for change.* Building Research Establishment, Watford, 2016.
9. Pelsmakers, S. and C.A. Elwell, *Suspended timber ground floors: Heat loss reduction potential of insulation interventions.* Energy and Buildings, 2017. **153**: p. 549-563.
10. Pelsmakers, S., et al., *Heat-flow variability of suspended timber ground floors: Implications for in-situ heat-flux measuring.* Energy and Buildings, 2017. **138**: p. 396-405.
11. STBA, *A Bristolian's guide to Solid Wall Insulation; Aguide to the responsible retrofit of traditional homes in Bristol*, B.C. Council, Editor. 2015, Sustainable Traditional Building Alliance: Bristol.
12. INCA, *Best Practice Guide External Wall Insulation*. 2015, Insulated Render and Cladding Association.
13. HM Government, *Heat and Buildings Strategy*, Department of Business Energy and Industrial Strategy, Editor. 2021, Crown Copyright: London.
14. HM Government, *Social Housing Decarbonisation Fund Demonstrator – successful bids*, Department for Business Energy and Industrial Strategy, Editor. 2021, Crown Copyright: London.
15. HM Government, *National Statistics, Energy consumption in the UK 2021*, E.a.I.S. Department of Business, Editor. 2021, Crown Copyright: London.
16. CIBSE. *CIBSE Weather Data Sets*. 2016 11/02/2020]; Available from: https://www.cibse.org/weatherdata.
17. Bonfigli, C., et al., *TM59: Design methodology for the assessment of overheating risk in homes*, K. Butcher, Editor. 2017, CIBSE: London.
18. CIBSE, *TM52: The limits of thermal comfort: avoiding overheating in European buildings*. 2013: London.
19. Glew, D., et al., *Thin Internal Wall Insulation (TIWI) Measuring Energy Performance Improvements in Dwellings Using Thin Internal Wall Insulation, Summary Report, BEIS Research Paper Number: 2021/016*, Department of Business Energy and Industrial Strategy, Editor. 2021, M Government, Crown Copyright: London.
20. Palmer, J., M. Livingstone, and A. Adams, *What does it cost to retrofit homes? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling*, Department for Business Energy and Industrial Strategy, Editor. 2017, HM Government: London.
21. HM Government, *National Energy Efficiency Data-Framework (NEED): Summary of Analysis, Great Britain, 2021*, E.a.I.S. Department of Business, Editor. 2021, Crown Copyright: London.

22. Gorse, C., et al., *Core cities Green Deal monitoring project.* Department of Buinsess Energy and Industrial Strategy, London, HM government, 2017.

This publication is available from: https://www.gov.uk/government/publications/demonstration-of-energy-efficiency-potential-deep

If you need a version of this document in a more accessible format, please email: alt.formats@energysecurity.gov.uk
Please tell us what format you need. It will help us if you say what assistive technology you use.