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DEEP Report 2.02

Case Study 17BG

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Executive summary

17BG was one of fifteen case study homes retrofitted in the DEEP project. The case studies were used to identify the performance of, and risks associated with, retrofitting solid walled homes. The data from the case studies was also used to evaluate the accuracy of modelled predictions around retrofit performance and risk.

The findings from this case study should be interpreted in the context of the house typology, which was relatively unusual in being a back-to-back home with a basement, and its existing condition, having already had some insulation. The performance and installation specifications of the retrofits, and the testing conditions are all described in the report. The case study provided useful insights; but more data, including that generated by the other DEEP case study dwellings, are needed to make broader generalisations for the housing stock.

In this case study, the cumulative airtightness, room-in-roof, floor, and wall retrofits were observed to reduce the home's heat transfer coefficient (HTC) by (98 ± 14) W/K, or (46 ± 4) %, according to coheating tests. The HTC reduction predicted by an Energy Performance Certificate (EPC) was 136 W/K (48 %). The predicted percentage reduction may appear to be in agreement, however, the absolute energy savings predicted by the EPC were almost double those that were measured, suggesting that predicted paybacks from EPCs can be misleading. Furthermore, the EPC predicted that almost half of the savings would be achieved by the room-in-roof retrofit, and almost half by the internal wall insulation (IWI). The measured data suggests that over half the savings came from airtightness improvements and over a quarter came from the IWI. This suggests that EPCs do not always accurately predict the savings for retrofits.

Investigations revealed that the accuracy of steady-state energy models, used to generate EPCs, could be improved when defaults for U-values, airtightness, and thermal bridging heat loss were replaced with measured and calculated values. When default data was replaced, and when simplifications around room-in-roof geometry were overridden, the home's pre-retrofit EPC band jumped from an E to a D and the post-retrofit band moved from a D to a C. Putting this into perspective, the improvement in input data improved the EPC by as much as the retrofits.

The case study further found that dynamic simulation models (DSM) predicted HTC values that were more closely aligned with measured results than steady-state alternatives used to create the EPC, though they still substantially overpredicted heat loss when default data were used. These findings reaffirm the relatively well understood dilemma that energy models, including EPCs, which rely on default data, are not able to accurately predict retrofit savings or payback.

Thermal bridging calculations were undertaken for the case study home, which found that 71 % of junctions in the uninsulated home had a risk of surface condensation, with greatest risk in the room-in-roof. The IWI and room-in-roof retrofits removed almost all risk, showing that there are benefits to insulation in homes beyond energy savings. However, risks were worsened where there were discontinuities in the insulation, e.g., missing insulation, or room-by-room retrofits.

Finally, it was observed that the retrofit reduced thermal bridging heat loss by more than 50 % for this home, and that the application of the same default bridging factor (y-value) to both pre- and post-retrofit led to important errors. In this case, the default y-value of 0.15 W/(m²·K) under predicted heat loss at the pre-retrofit stage (y = 0.20 W/(m²·K)), but over predicted heat loss when fully retrofitted, (y = 0.08 W/(m²·K)). This suggests that the application of y-value defaults may need revision.

1 Introduction to 17BG

Case study 17BG is a two-bed pre-war solid walled dwelling. As it is a back-to-back style end-terrace home, its interesting features include having a room-in-roof and a large amount of party wall. Some improvements had been made in the home before the DEEP retrofits took place, including thin internal wall insulation (TIWI). Staged retrofits were cumulatively installed at the house to reflect the common piecemeal approach, including airtightness improvements, room-in-roof insulation, suspended ground floor insulation and internal wall insulation (IWI). Following these, a final stage to incorporate a whole house approach to the retrofit was undertaken. The case study provided the opportunity to explore the risks and performance impacts of a room-by-room approach to IWI (an approach typically adopted by landlords) and common discontinuities in the room-in-roof retrofit at hard-to-treat areas.

1.1 DEEP field trial objectives

17BG is one of fourteen DEEP case studies, which, collectively, attempted to investigate the research objectives listed in Table 1-1, though not all the objectives were 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 the impact of different options including achieving EPC band C.
Fabric vs ventilation	Insulation influences fabric and 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 the DESNZ, the wider DEEP Steering Group, and expert QA panel, additional questions were proposed. The objectives were refined to develop seven discreet research questions. These are listed below and used in 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 17BG will contribute to the formation of a body of evidence from the DEEP project, that will begin to address these questions.

1.3 Case study house information

Shown in Figure 1-1, 17BG is a two-bedroom property in Leeds, West Yorkshire, and was built around 1890. External walls are constructed from solid nine-inch brick and, although it is a back-to-back property (i.e.,has a neighbour to the sides and rear), it is an end-terrace so has two external walls (front and gable). Entry is directly into the living room, with the kitchen also on the ground floor. Stairs up to the middle floor (comprising bedroom 1 and bathroom) are at the rear of the living room. Stairs down to the basement, which spans part of the ground floor, are accessed through the kitchen. Bedroom 2 is in the roof. While the living room and bedroom 1 have chimney breasts, they are sealed, and the chimney stack has been removed, so this does not provide any purpose-provided ventilation.

This is a typical construction and archetype for the area, though less so nationally. There are over five and a half million pre-1918 homes in England and Wales [1] and two-bed terraced houses make up around 9 % of all homes [2]. This is equivalent to around half a million homes, although many may not have basements, rooms-in-roof (RIR), or rear neighbours. It is not clear, therefore, if the results obtained from 17BG will be necessarily representative to equivalent through-terrace homes. These features of the case study do, however, enable the research to explore a deeper understanding of fabric and ventilation heat loss interactions and may provide an insight into the issues also experienced by low rise flats.

Figure 1-1 Case study house

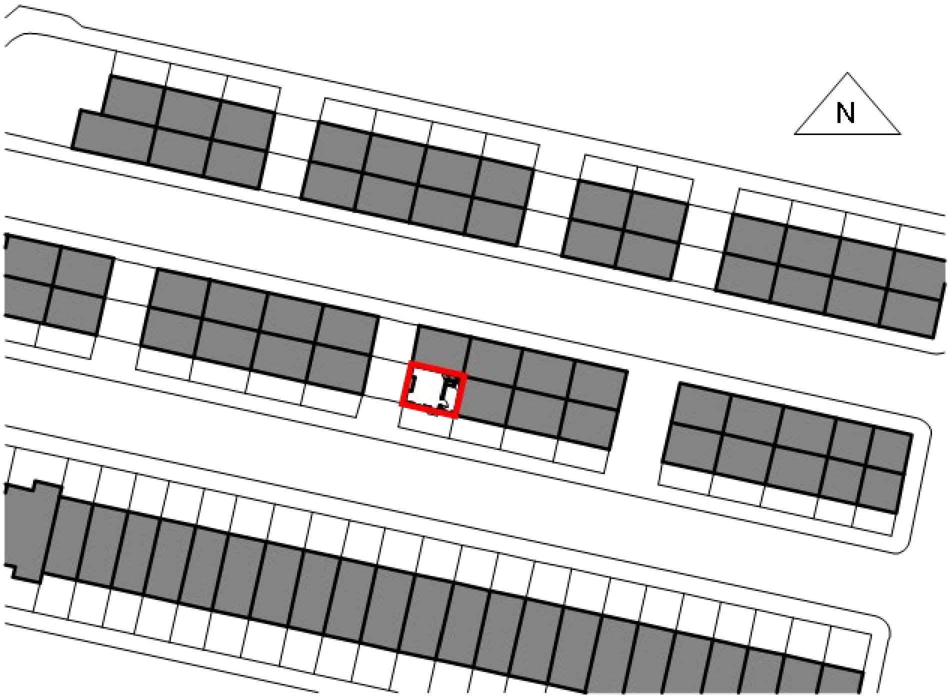

Figure 1-2 Case study house site location plan

Floor plans, elevations, and sections can be seen in Figure 1-3, Figure 1-4 and Figure 1-5 respectively.

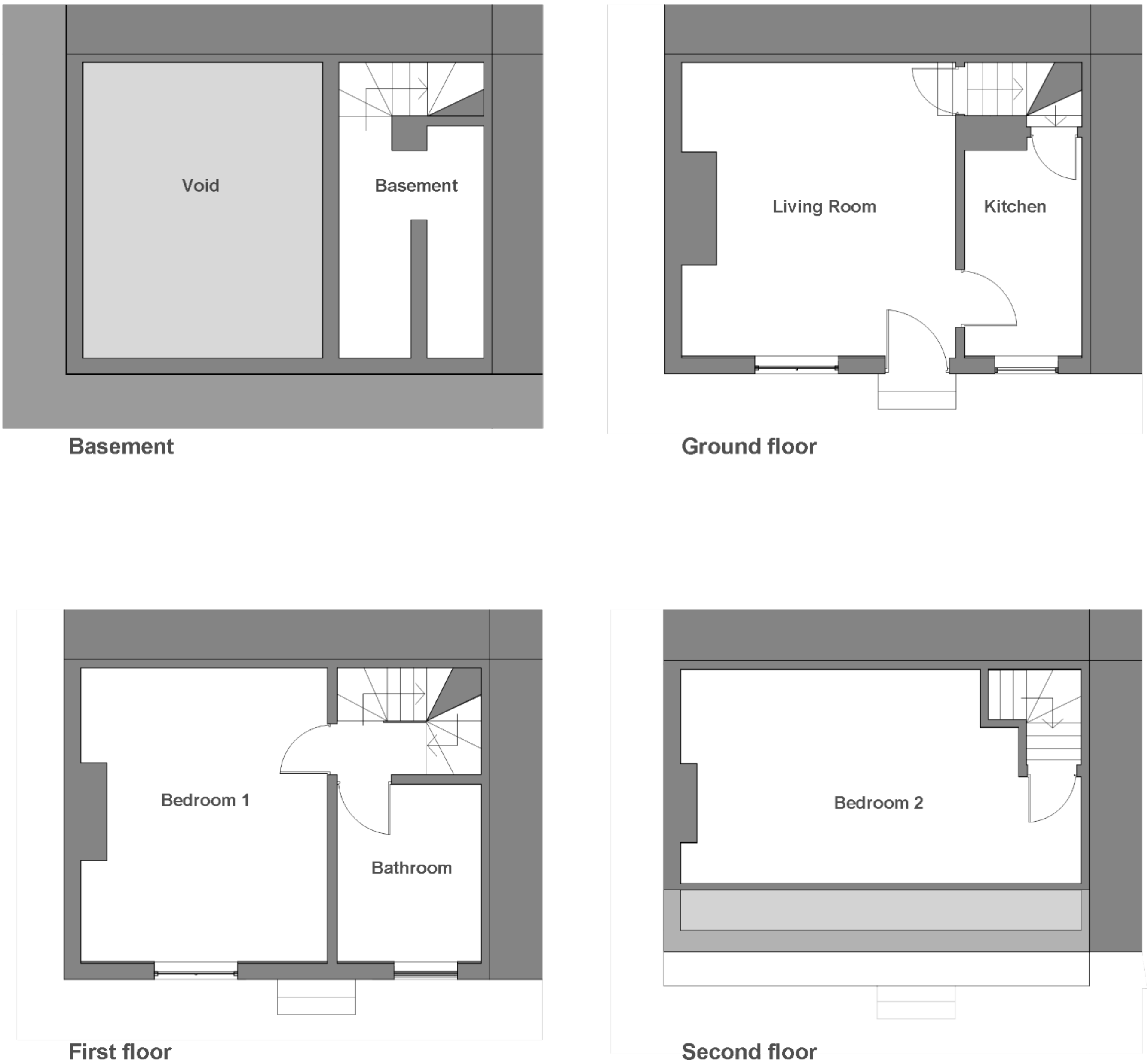

Figure 1-3 House floor plans

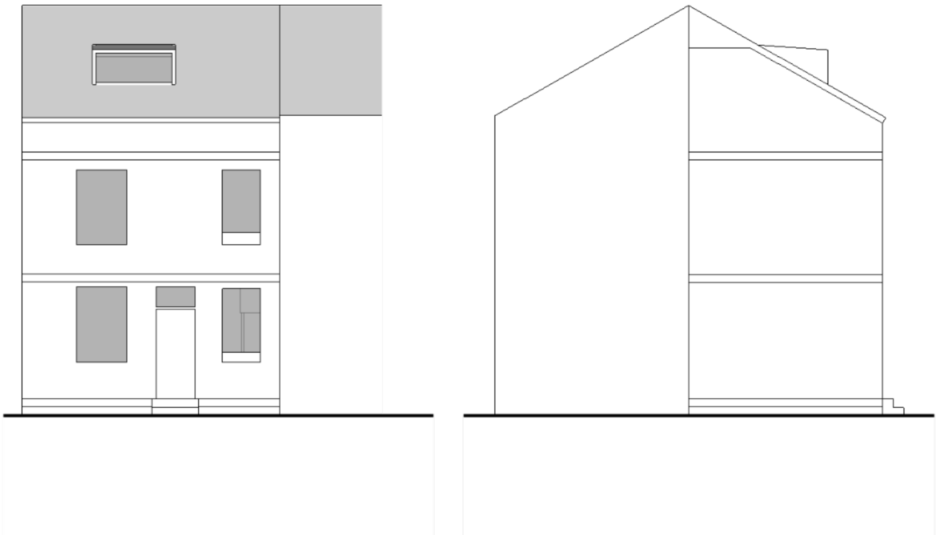

Figure 1-4 Front and side elevations

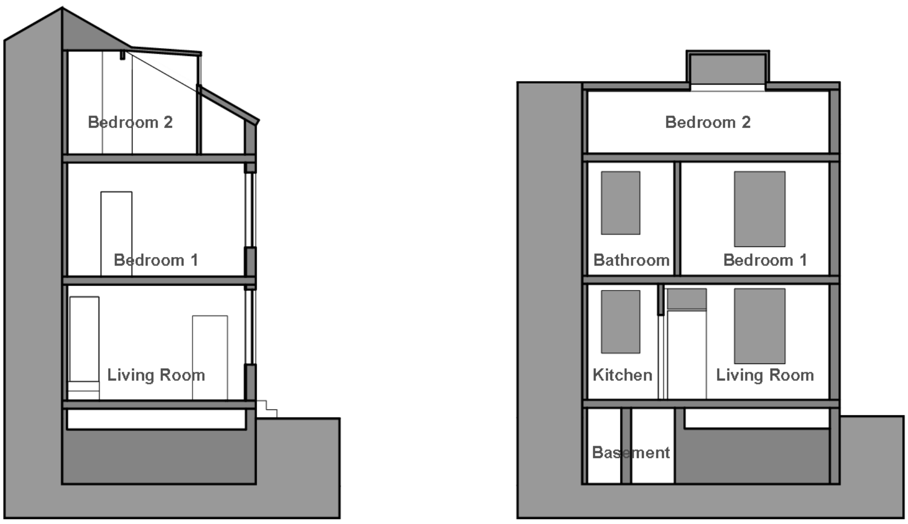

Figure 1-5 Sections through case study house

The dimensions of each element in the home are listed in Table 1-2 and 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	*177.6 m³*
Total floor area	*64.7 m²*
Total heat loss area	*128.6 m²*
Ground floor	23.3 m²
Gable external wall, excluding chimney	19.8 m²
Chimney external wall	17.0m²
Front external wall	22.8 m²
Windows	8.6 m²
Door	1.9 m²
Sloping roof	7.8 m²
Ceiling to loft void	7.7 m²
Party wall rear	47.2 m²
Party wall side	30.8 m²
Dormer roof	3.1 m²
Dormer cheek	1.0 m²
Knee wall	9.8 m²
Ceiling to eaves void	5.9 m²

Construction details are summarised in Table 1-3. Features to note, illustrated in Figure 1-6:

- Thin IWI (≈ 20 mm) was already installed on the front external wall facing the street, though not on the gable wall
- Bedroom 2 (room-in-roof) was partially insulated prior to the retrofits. This comprised mineral wool loft insulation in the eaves above bedroom 1 (which could be accessed through a small panel in the knee wall), and between the ceiling joists of the flat roof elements (which were inaccessible).
- Polyisocyanurate (PIR) boards were also found between rafters in the sloping ceiling.

Other than these insulated areas, the property had not undergone any other fabric retrofits. There were no obvious defects, and the property was not noticeably damp, although the basement air was humid (RH > 80 %). This may be due to the lack of through ventilation across a back-to-back dwelling. The windows and doors were in working order and providing adequate seals, so were excluded from the whole house approach 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 in Table 1-3 were calculated using the BRE calculator and were 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 to calculate the impact of repeating thermal bridges on each plane element calculation (e.g., floor joists).

Table 1-3 Construction and retrofit summary

Detail	Original construction	Retrofit[1]
Airtightness	15 $m^3/(h.m^2)$ @ 50 Pa	General sealing of air leakage paths
Roof	Room-in-roof with partial insulation including 100 mm mineral wool in ceiling to eaves	a. XPS between timbers of knee walls 75 mm x 0.033 W/(m·K) Target U-value 0.40 W/(m²·K) b. IWI Woodfibre board 72 mm x 0.043 W/(m·K) Target U-value 0.44 W/(m²·K) c. Mineral wool in dormer cheeks 40 mm x 0.044 W/(m·K) Target U-value 0.81 W/(m²·K)
Floor	Uninsulated suspended timber	Mineral wool between joists 200 mm x 0.044 W/(m·K) Target U-value: • 0.18 W/(m²·K) (Kitchen) • 0.20 W/(m²·K) (living room)
Wall type 1 (Gable)	Uninsulated 9-inch solid brick	IWI Woodfibre board (Ground floor and First floor) 52 mm x 0.043 W/(m·K) Target U-value 0.56 W/(m²·K)
Wall type 2 (Front)	9-inch solid brick insulated internally with approx. 20 mm Polystyrene backed plasterboard	Existing IWI removed IWI Woodfibre board 52 mm x 0.043 W/(m·K) Target U-value 0.55 W/(m²·K)
Windows	uPVC Double glazed	None
Door	Composite	None
Whole house approach	a. Exclude Insulation to kitchen and bathrooms (common	a. IWI Woodfibre board to kitchen and bathroom 52 mm x 0.043 W/(m·K)

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

Detail	Original construction	Retrofit[1]
	landlord property maintenance approach) b. Exclude Insulation to RIR sloping ceiling (contractor assumed adequate insulation) c. Exclude Insulation to RIR loft (contractor assumed adequate insulation plus no loft hatch to access) d. Exclude Insulation to RIR dormer roof (contractor assumed adequate insulation) e. Exclude Insulation to RIR dormer cheek	Target U-value 0.55 W/(m·K) b. Woodfibre to sloping ceiling 50 mm x 0.038 W/(m·K) between rafters 40 mm x 0.041 W/(m·K) on top of rafters Target U-value 0.49 W/(m²·K) c. Mineral wool to flat ceiling 200 mm x 0.044 W/(m·K) Target U-value 0.22 W/(m²·K) d. Woodfibre to dormer ceiling 40 mm x 0.038 W/(m·K) between rafters Target U-value 0.81 W/(m²·K) e. IWI Mineral wool on dormer cheeks 40 mm x 0.043 W/(m·K) Target U-value 0.65 W/(m²·K)

The sequence of the staged whole house retrofit approach is shown and illustrated, in Figure 1-6 through to Figure 1-10. Building performance evaluation (BPE) tests, whole house energy modelling and elemental thermal simulations were conducted at each retrofit stage to quantify changes in energy performance and the potential for condensation risk. The specific methodologies for these are described in the DEEP Methods 2.01 Report.

The codes in Table 1-4 are shorthand to identify each retrofit stage to aid the discussion and presentation of results. As the retrofits were cumulative, the codes are combined to explain which stage is being discussed, e.g., the final code for stage 5 is 17BG.A.R.F.W. The intention of stage 6 is to quantify impact on energy performance and moisture risks, of the activities that should take place as part of a whole house approach to retrofit. This approach is discussed in PAS2035. Consequently, the case study home at this stage would be referred to as 17BG.A.R.F.W.WH.

Table 1-4 Phased retrofit stages

	Retrofit stage	Code	Retrofit dates
1	Baseline	B	February 2020
2	Airtightness improvements	A	March 2020
3	Room-in-roof insulation	R	September 2020
4	Suspended timber ground floor insulation	F	November 2020
5	Internal wall insulation (IWI)	W	December 2020
6	Whole house approach	WH	January 2021

The order in which the retrofits were undertaken is shown in Figure 1-6 to Figure 1-10, and was selected to investigate each improvement that may be achieved without installing IWI, and to some extent, which retrofits may be more likely to take place in homes. By assessing the reductions in terms of W/K, the success of each of the fabric improvements can be evaluated independently, regardless of which order they are undertaken.

2.02 DEEP 17BG

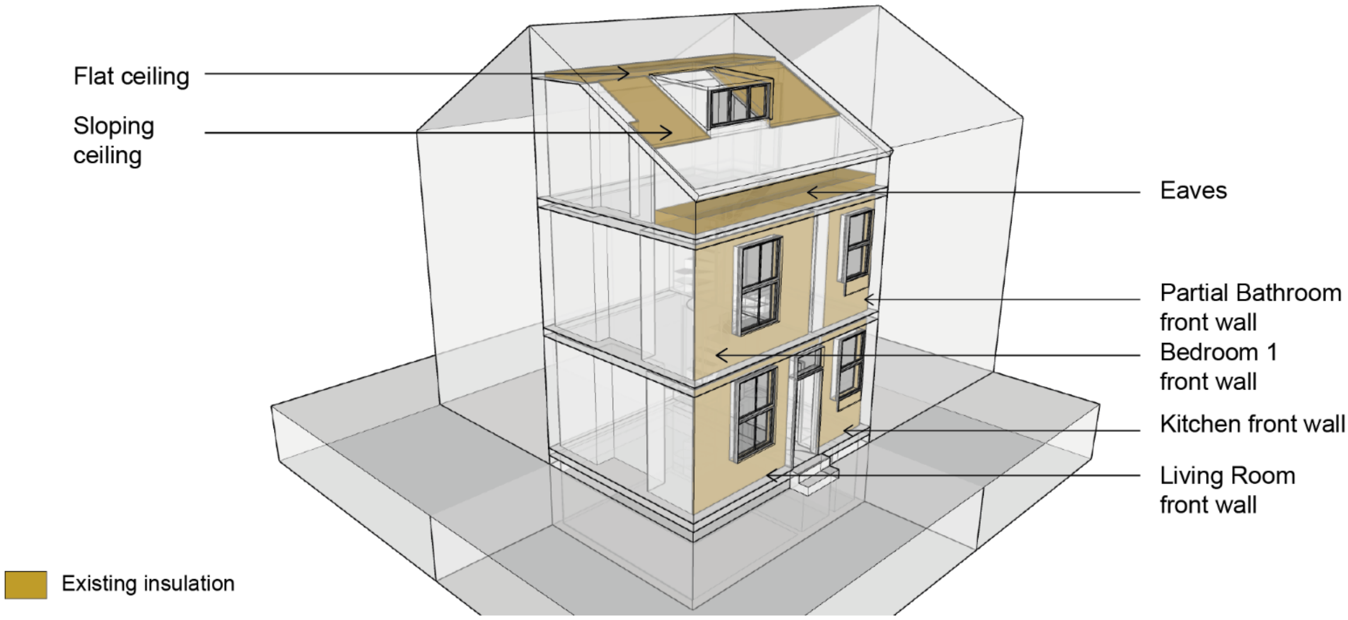

Figure 1-6 Stage 1: Insulation already in the property prior to the retrofits (17BG.B)

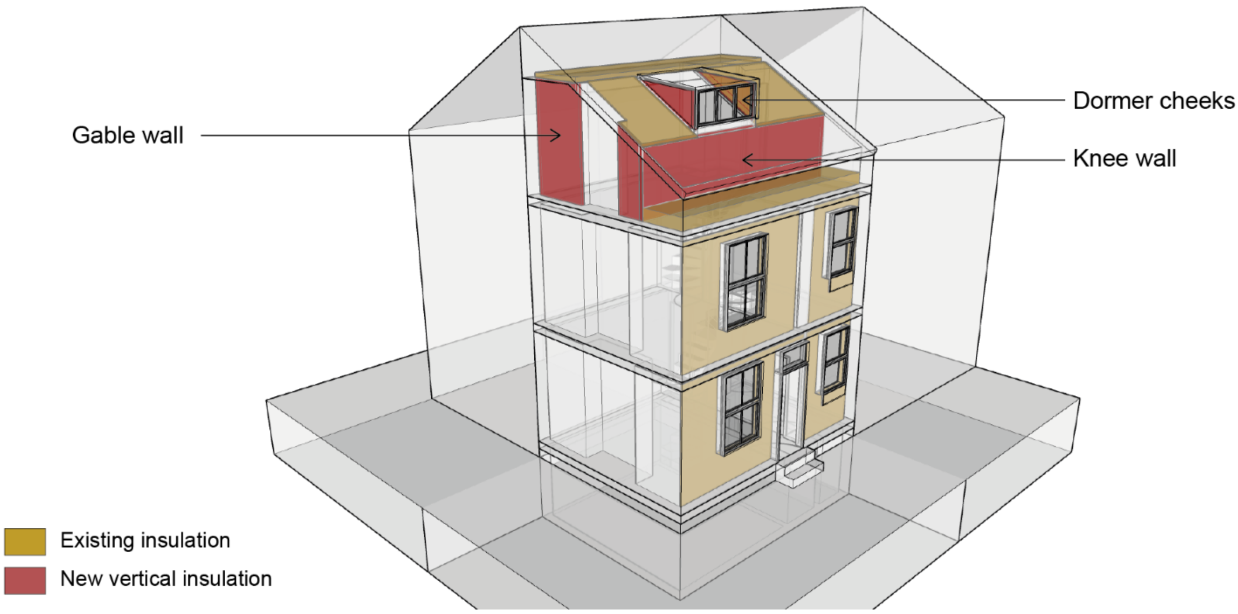

Figure 1-7 Stage 2: Roof retrofit to Bedroom 2 (17BG.A.R)

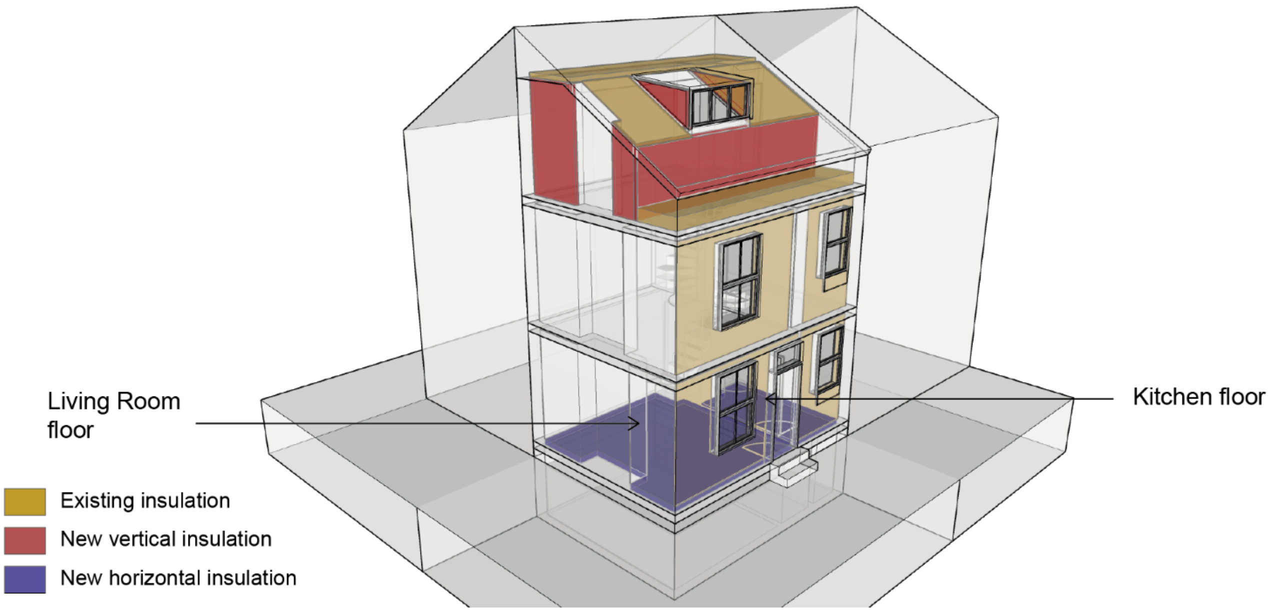

Figure 1-8 Stage 3: Floor retrofit to kitchen and living room, (17BG.A.R.F)

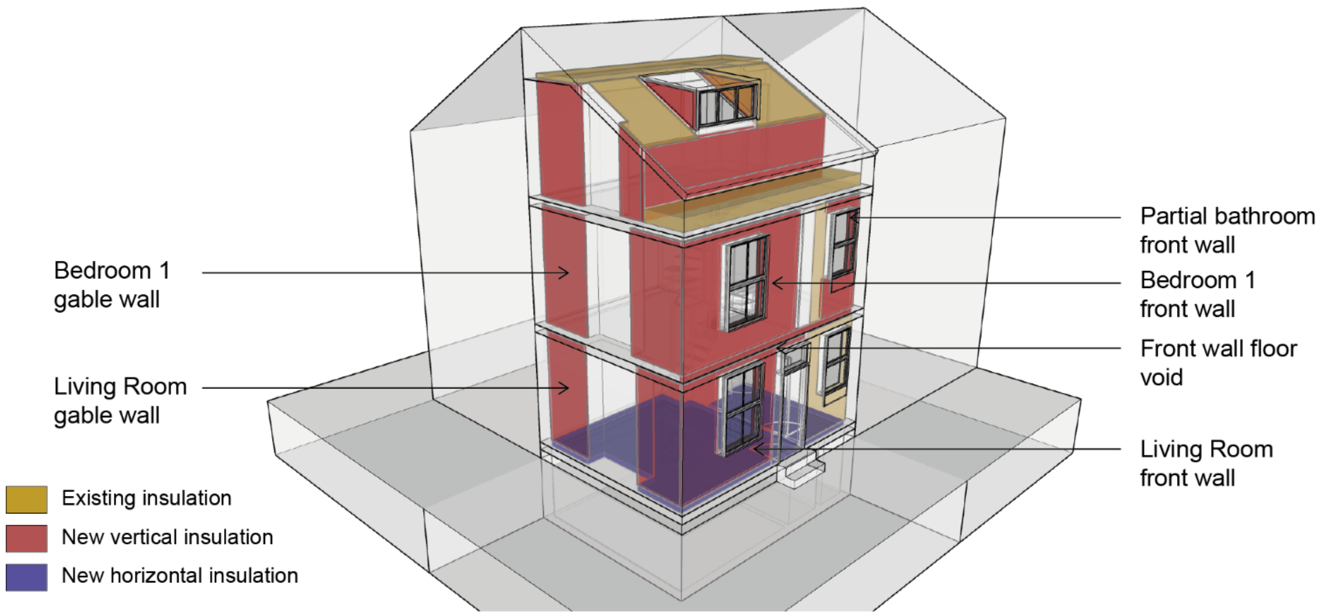

Figure 1-9 Stage 4: IWI retrofit to ground and first floor external walls (17BG.A.R.F.W)

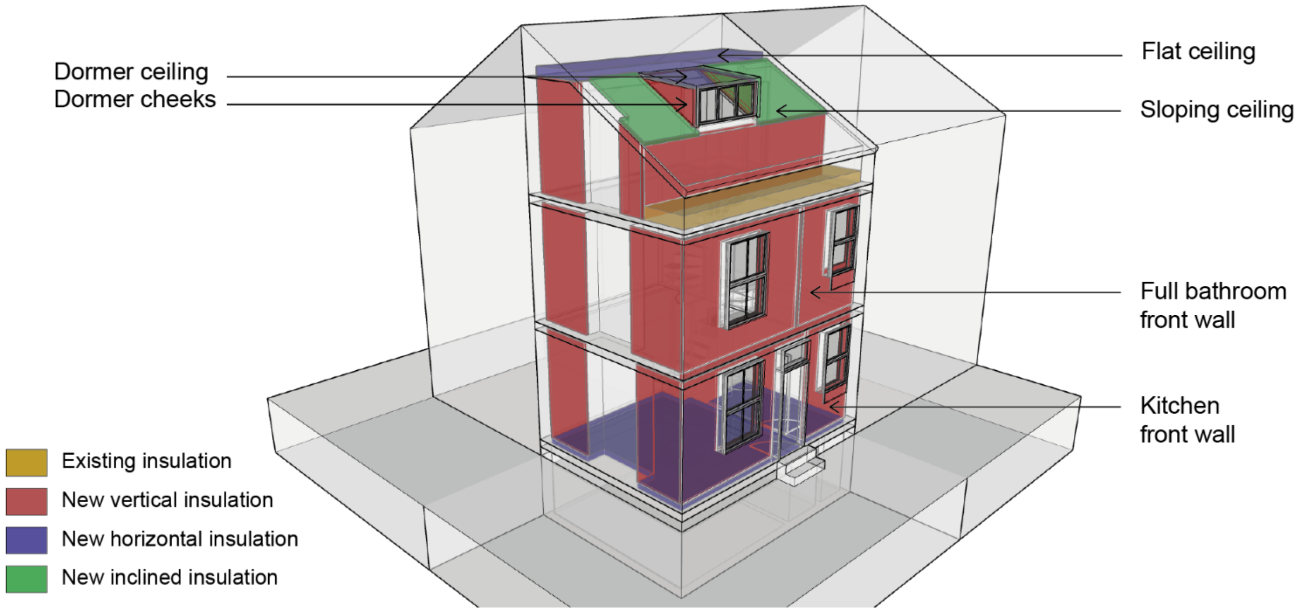

Figure 1-10 Stage 5: Whole house approach retrofit (17BG.WH)

Case study and retrofit summary

17BG provided an opportunity to investigate the impact of a whole house retrofit, on a case study end-terrace, solid walled, back-to-back property, built in the 1890s.

It collected performance and moisture risk data on relatively less common retrofits including airtightness, rooms-in-roof, suspended timber floor, and IWI.

It also provided the potential to investigate the risks and performance implications of room-by-room approaches, which are often favoured by landlords.

2 Fieldwork and modelling methods

BPE tests and modelling activities were undertaken on 17BG at each retrofit stage in accordance with the methodologies listed in the DEEP Methods 2.01 Report. This section outlines the specific implementation of these methods at 17BG, including variations.

2.1 Environmental data collection

Internal environmental data logging equipment is described in detail in the DEEP Methods 2.01 Report. Internal environmental data collected at 17BG included air temperature, Relative Humidity (RH) and CO_2 levels. External environmental data was collected via a weather station located on the Leeds Beckett University Rose Bowl building, located approximately 1 mile from 17BG, and included vertical solar irradiance, air temperature, and wind speed. This was supplemented by an external air temperature sensor positioned outside 17BG.

2.2 Measured survey

A detailed survey of the building was undertaken. From this, a digital version of the house was developed using SketchUp, which was used to calculate dimensions for each element and to draw up the plans shown in Figure 1-3. Plans, sections, and elevations were directly exported 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 for lab analysis of the material properties and to identify the construction layers, as per the method described in the DEEP Materials 4.0 Report.

2.3 Airtightness and thermography

Blower door tests were completed at all baseline and retrofit stages. Results from these were used to identify changes related to the retrofits and to estimate heat loss attributable to air leakage, or the heat transfer coefficient (HTC) for background ventilation (HTC_v). Qualitative thermography surveys under depressurisation were completed and additional thermography of specific details, under normal conditions, were captured to identify changes between each retrofit stage. Low pressure Pulse air tests and CO_2 tracer gas tests were also deployed during the testing program to compare with the blower door tests results.

Ventilation in the home was provided via trickle vents and this was not altered during retrofits. The interaction between infiltration and ventilation is complex; it was beyond the scope of the DEEP project to undertake in-use monitoring of internal air quality under occupied conditions; this would have required longitudinal conditions monitoring pre- and post-retrofits.

2.4 Heat flux density measurement and U-values

Twenty heat flux plates (HFPs) were installed on different elements in 17BG to measure the baseline in-situ U-values, measure improvements achieved by the fabric upgrades, quantify party wall heat exchange, calibrate energy and thermal models, and estimate the fabric heat loss (HTC_f). These were compared with coheating tests and HTC disaggregation. The HFP locations are listed in Table 2-1 and for context, the location of these are visualised in Figure 2-1, Figure 2-2 and Figure 2-3. Thermography was undertaken to identify the most representative location for each fabric element and multiple locations for each element were measured where possible.

Table 2-1 HFP locations

HFP	Element	Room
T1	External wall front	Living room
M1	External wall front	Bedroom 1
M2	External wall gable	Bedroom 1
N3	External wall gable	Bedroom 2
N4	External wall gable	Bedroom 2
T2	External wall chimney breast	Bedroom
T3	Rear party wall	Living room
M3	Rear party wall	Bedroom
N5	Rear party wall	Room-in-roof
T4	Neighbour party wall	Kitchen
M5	Neighbour party wall	Bathroom
T5	Suspended ground floor	Living room
M4	Ceiling to room-in-roof eaves	Bedroom
O1	Sloping ceiling	Room-in-roof
O2	Sloping ceiling	Room-in-roof
O3	Dormer cheek	Room-in-roof
O4	Dormer roof	Room-in-roof
N1	Knee wall	Room-in-roof
N2	Knee wall	Room-in-roof
O5	Flat roof	Room-in-roof

Heat flux density from individual HFPs, along with internal and external air temperature data, were used to calculate U-values for each element. Where more than one HFP was located on a single element, a simple average was used. Where a repeated thermal bridge was measured (such as a floor joist for example), or an area of non-representative heat flux density was observed, a weighted average was calculated to provide the whole element U-value estimates.

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. Similarly, where areas of thermal bridging were 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. This was especially important since 17BG was a relatively small house with few large, uninterrupted surface areas.

While the BRE calculator has the capacity of calculating the U-value of windows, it requires manufacturer's details of the window component parts including the glazing U-Value, the frame U-value and the internal construction to estimate the linear Ψ-value. These details were not available and so the U-values for the windows had to be assumed, representing an area of uncertainty in the energy models.

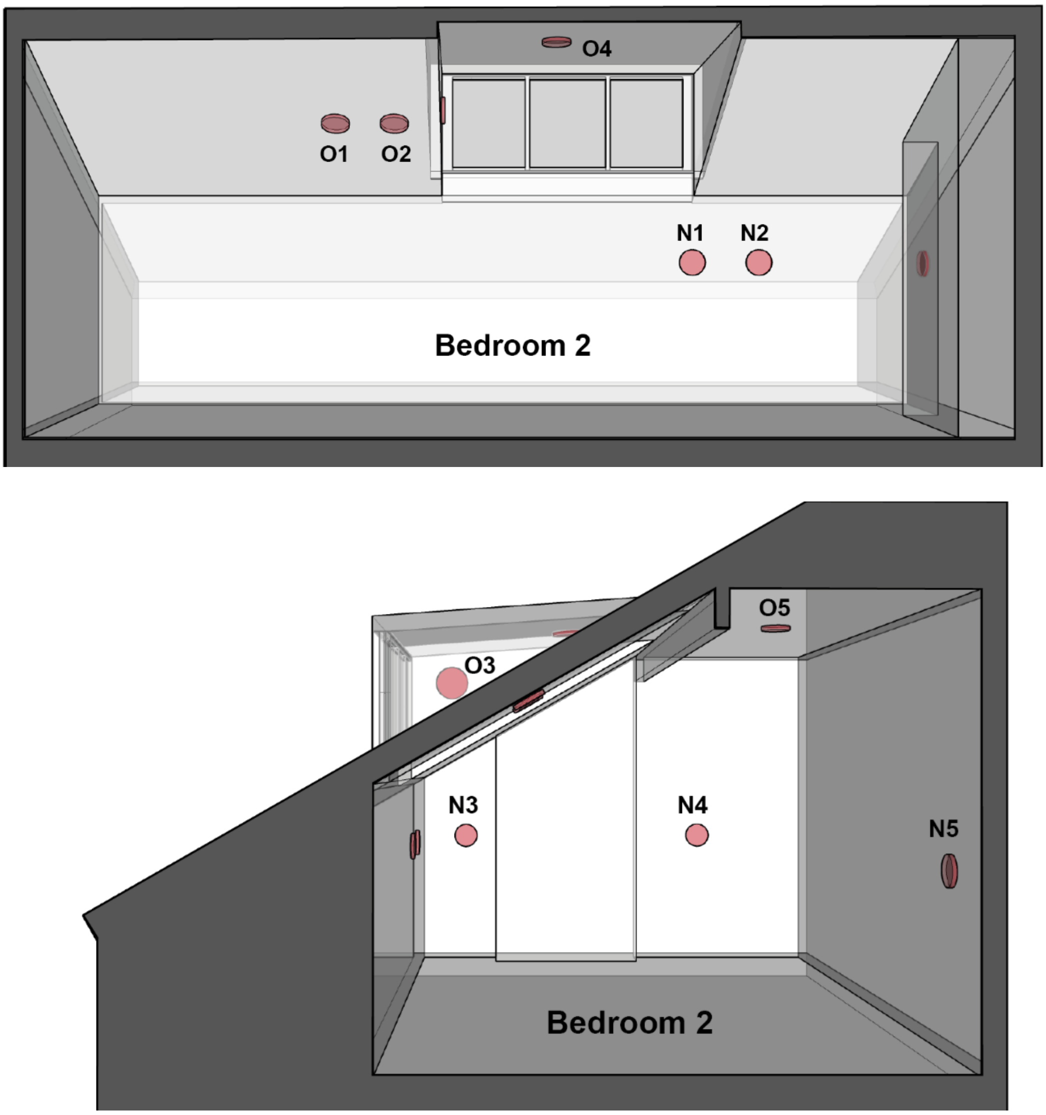

Figure 2-1 Room-in-roof HFP locations

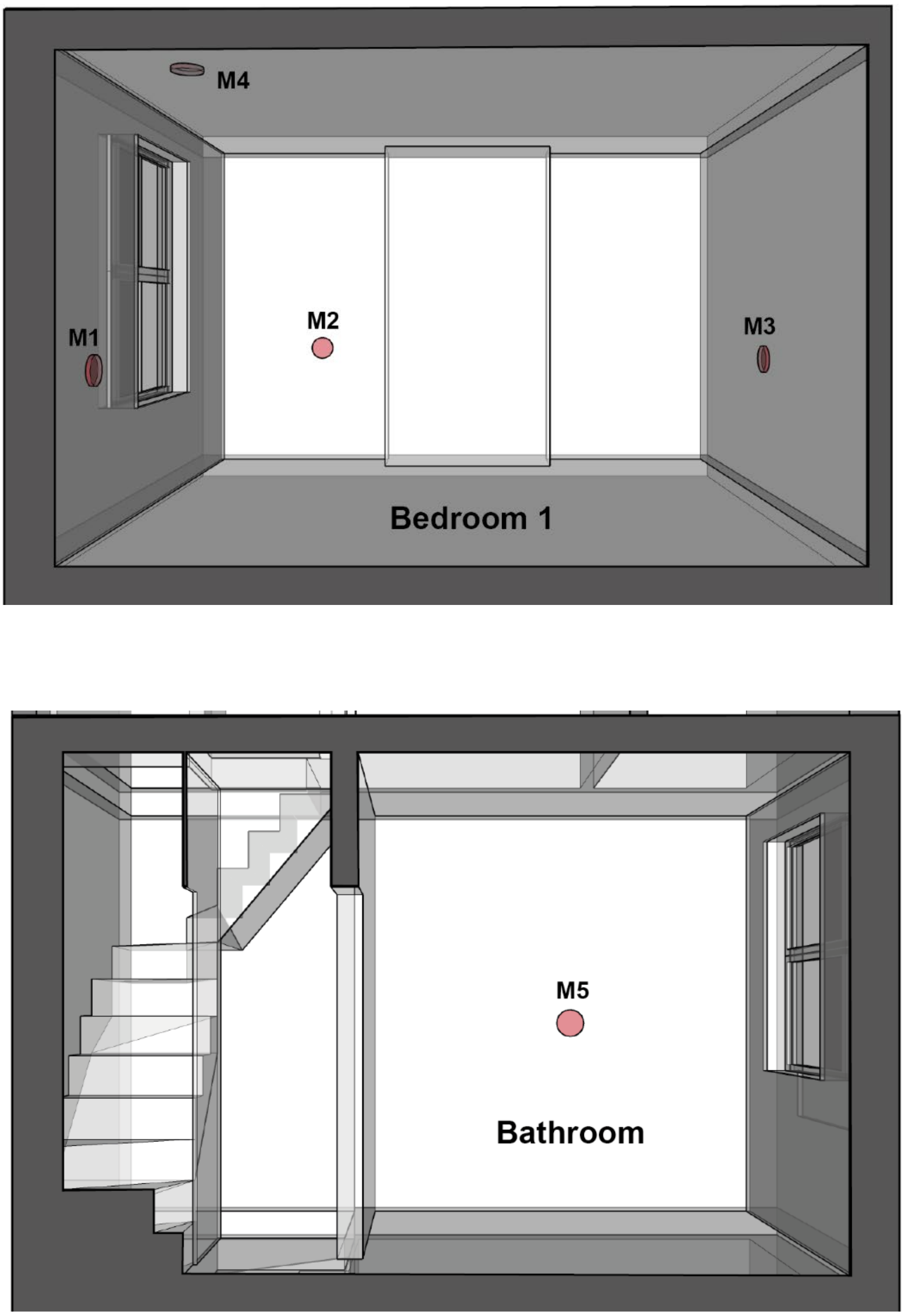

Figure 2-2 First floor HFP locations

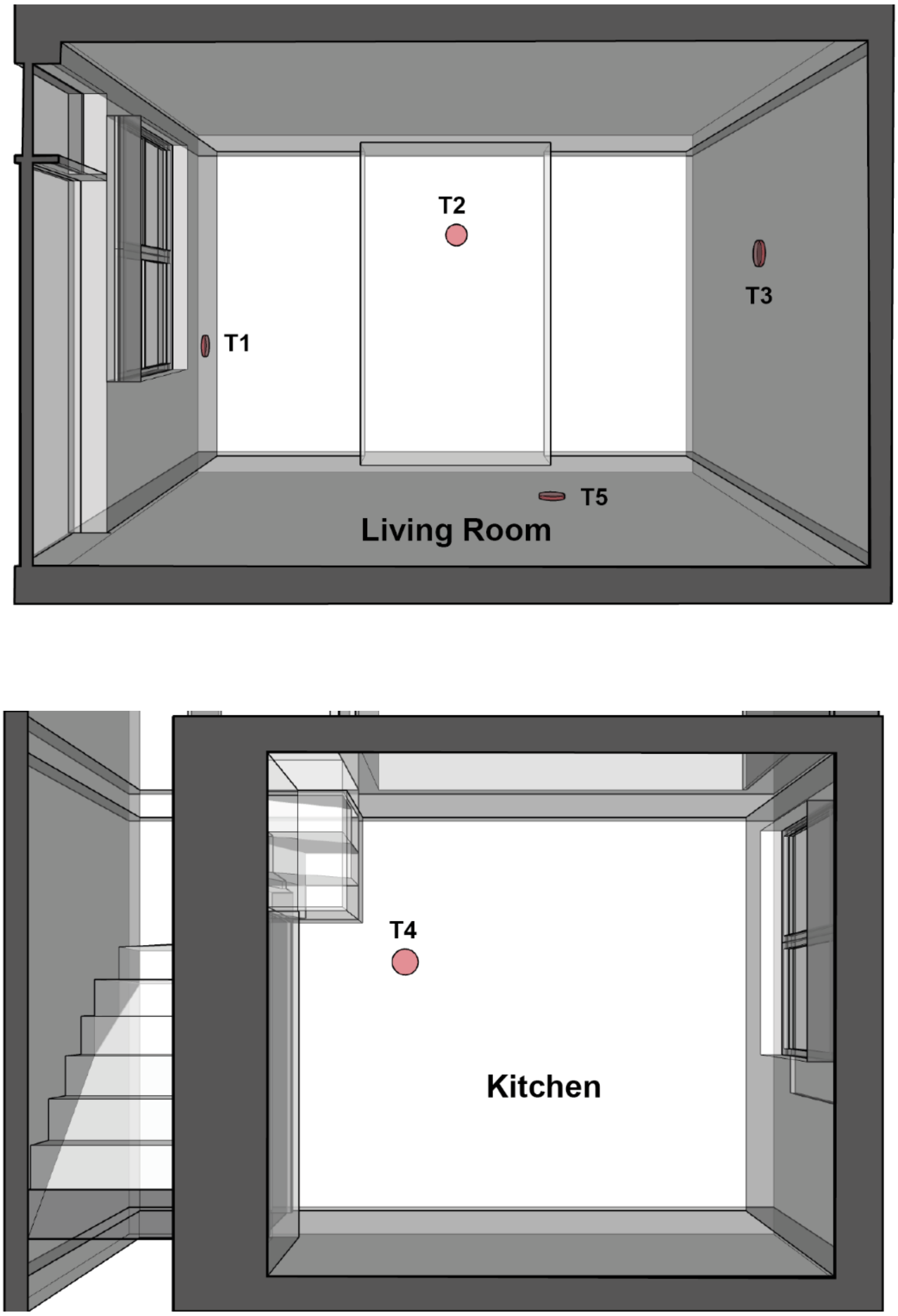

Figure 2-3 Ground floor HFP locations

2.5 Whole house heat transfer coefficient (HTC)

Coheating tests were performed at each stage of the retrofit, as described in the DEEP Methods 2.01 Report, 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 17BG where there was risk of thermal bridging and where surface temperatures were measured to calculate the temperature factor (f_{Rsi}) to assess surface condensation risk. These are described in the results section and summarised here:

- Kitchen and bathroom external wall to identify the risks associated with a room-by-room IWI approach
- Front wall to gable wall junction
- Window jamb and sill
- Intermediate floor
- Rear party wall junction

2.7 Whole building energy modelling

The modelling methodologies undertaken are explained in detail in the DEEP Methods 2.01 Report. DEEP first uses 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 compares how these restrictions affect the HTC that BRDEM predicts. These are also compared with HTC predicted by DSM (using DesignBuilder software version 7.0.0.088 [3]) 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 stages

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

[2] Provided by Appendix S RdSAP 2012 version 9.94
[3] Provided by Appendix K RdSAP 2012 version 9.94
[4] Derived from Blower door test
[5] Derived from BRE Calculator
[6] Derived from heat flux plate measurements
[7] Calculated from TRISCO bridging simulations

Additionally, the models predicted annual energy demand, annual heating cost, carbon dioxide emissions, SAP score, and EPC band. The success of the retrofits against these criteria could therefore be evaluated and, along with the retrofit install costs, simple payback periods for each retrofit calculated.

By learning about the variability of the different models and how they compared to measured data in real cases, recommendations may be possible for improvements to both the models and the ways they are utilised. Improving understanding of modelling uncertainty may lead to more 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 thermal bridging heat losses in the case study dwelling before and after retrofits. The modelling procedure is described in detail in the DEEP Methods 2.01 Report. Modelling the Ψ-value of junctions allows the thermal bridging heat loss (HTC_b), 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 (f_{Rsi}) for each of the junctions that may exist in the house pre- and post-retrofit, and where different retrofit strategies are considered, meaning it is able to compare the risks associated with piecemeal vs whole house retrofits.

In this case study, thermal bridging calculations were performed for all 32 different junctions under the five different retrofit scenarios. Material properties were taken from standard RdSAP values, but where measured values were available, they were used in addition to standard values and a comparative analysis undertaken. Some additional retrofit scenarios were included that were not actually undertaken at 17BG, to also assess the risk of alternative retrofit designs. This resulted in 144 different models which are described in detail in the results section.

Case study method summary

A deep dive into the 17BG retrofit case study was undertaken involving coheating tests, blower door tests, and 20 heat flux density measurements on fabric elements, taken before and after each of five 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 32 different junctions in the house under the different retrofit 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 details 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 to predict these.

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 test. It then describes how modelled predictions compared with the measured data and how successful five different calibration steps were at improving predicted heat loss, including assessing thermal bridging. The model outputs are discussed in terms of their implications for EPCs, space heating, CO_2 emissions, fuel bills, and paybacks. Finally, the potential surface condensation risks posed in the house at each retrofit stage were discussed.

The results of the in-situ measurements and modelling are presented here. Findings from each retrofit stage are presented, followed by a discussion around retrofit cost and risks.

3.1 Airtightness improvements

In its original condition, the air permeability of 17BG was found to be relatively high at 15.3 $m^3/(h.m^2)$ @ 50Pa. Improvements were undertaken, reducing this by 40 % down to 9.2 $m^3/(h.m^2)$ @ 50Pa. For context, the average UK air permeability is estimated to be approximately 11 $m^3/(h.m^2)$ @ 50Pa [4] and the limiting value permitted under Building Regulations for new build dwellings is 8 $m^3/(h.m^2)$ @ 50Pa or 1.57 $m^3/(h{\cdot}m^2)$ @ 4Pa [5, 6] according to the 2021 Approved Document L [5,6]. Thus, it was brought in line with new build standards for airtightness at the time, but not with subsequent changes to air permeability limiting values.

It is important to note that permeability is not the same as ventilation for fresh air, for which there were trickle vents on windows and mechanical extract fans in the bathroom and kitchen. These were retained throughout the retrofit but sealed during testing.

Some of the main air leakage routes identified are shown in Figure 3-1, Figure 3-2, and Figure 3-3 including:

- At the edges of and through the suspended timber ground floor
- Around the cellar door
- Behind the existing IWI (linking potential air movement routes)
- At the perimeter of the intermediate floors
- Via penetrations in the building fabric around services (waste pipes etc.)

The unsealed penetrations created a direct air exchange with the outside. The suspended timber ground floor was unsealed, with gaps between and around the floorboards allowing air exchange with the basement and floor void. Air movement behind the IWI suggests that perhaps airbricks had not been sealed effectively, and that the IWI had also not been fully sealed to the wall, linking this void to other voids and gaps, allowing the potential for thermal bypasses.

Finally, air leakage via the intermediate floor voids, which was observed to be close to external temperatures under –50 Pa depressurisation, suggests air exchange between these voids with small cavities between stretcher courses in the external walls and gaps around the ends of built-in joists.

Figure 3-1 Base case infiltration through the suspended timber ground floor at wall junction and behind the existing IWI during depressurisation

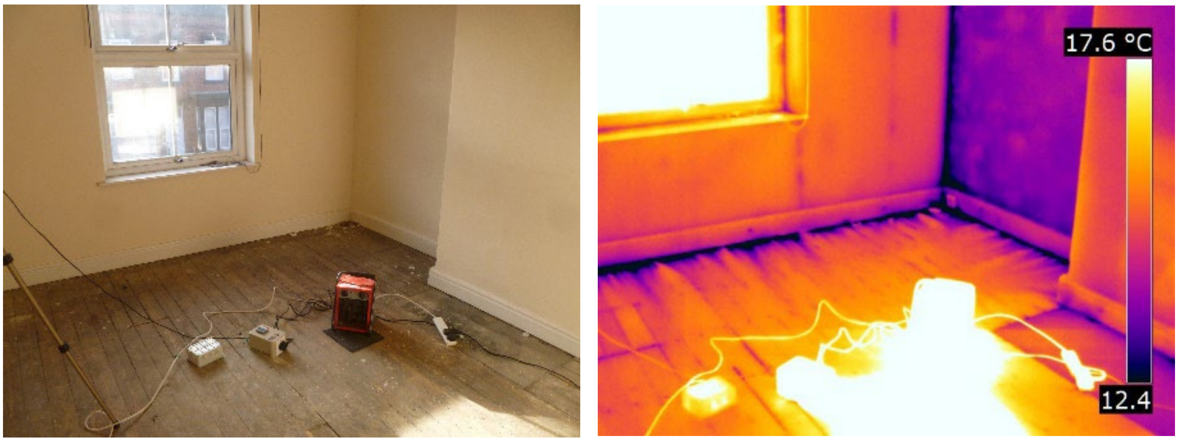

Figure 3-2 Base case infiltration through the intermediate floor at the external wall junctions during depressurisation

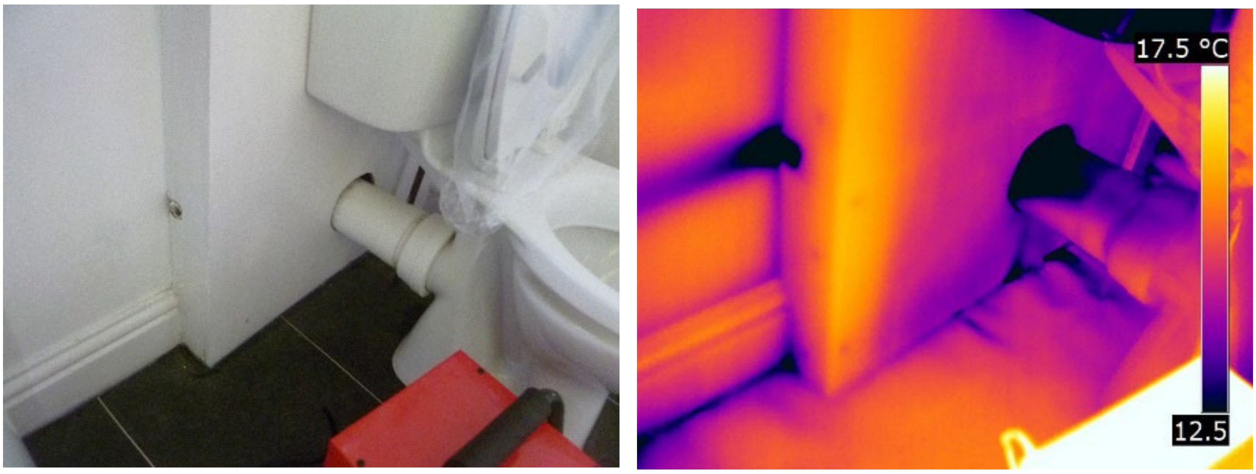

Figure 3-3 Base case infiltration via service penetrations on the external wall during depressurisation

Based on these observations, the airtightness improvement strategy adopted was to seal or more effectively ‘box in’ penetrations through the external wall, as well as sealing up air bricks that were not deemed necessary for providing fresh air, including in the basement.

Air bricks were visible on the outside of the house but had been covered over on the inside by a previous thin IWI retrofit. It is not known when this retrofit took place or under what standards. Therefore, it is not possible to tell if this was an attempt to improve the airtightness of the building after establishing that there was adequate ventilation, or if it was unintentional, and so not part of a considered whole house ventilation strategy.

It should be noted that even without these air bricks, uncontrolled ventilation (infiltration) was still excessive in the pre-retrofit case. A lack of ventilation was therefore not considered a concern, as trickle vents were present on all windows, as were mechanical extracts in the kitchen and bathroom, even though the back-to-back construction limited through ventilation.

In the other retrofit stages, no additional attempts were made to specifically address airtightness. This was done to replicate a piecemeal retrofit (as opposed to a whole house approach) so that any incidental change in infiltration rate resulting from the other retrofits relates to the relationship between airtightness and fabric improvements. Airtightness at each retrofit stage was recorded and is discussed in the following section.

3.1.1 Impact of retrofits on airtightness

The reduction in airtightness achieved by each retrofit stage is presented in Figure 3-4.

Overall, the airtightness of the house has been reduced by one third, bringing it in line with newbuild standards. Of all the retrofits, only the specific airtightness phase achieved a meaningful airtightness improvement, though some moderate savings appear to have been made during the 'whole house approach', final stage. This was due to insulation and a plaster skim being applied to the sloping ceiling in the room-in-roof, though this reduction was within the uncertainty of the test method. The specific airtightness retrofit improvements are discussed in more detail below.

The order in which these retrofits were undertaken may also affect the potential savings achieved. However, as will be shown, the majority of the reduction in air leakage was achieved by sealing around penetrations, so may not have been affected by the retrofits.

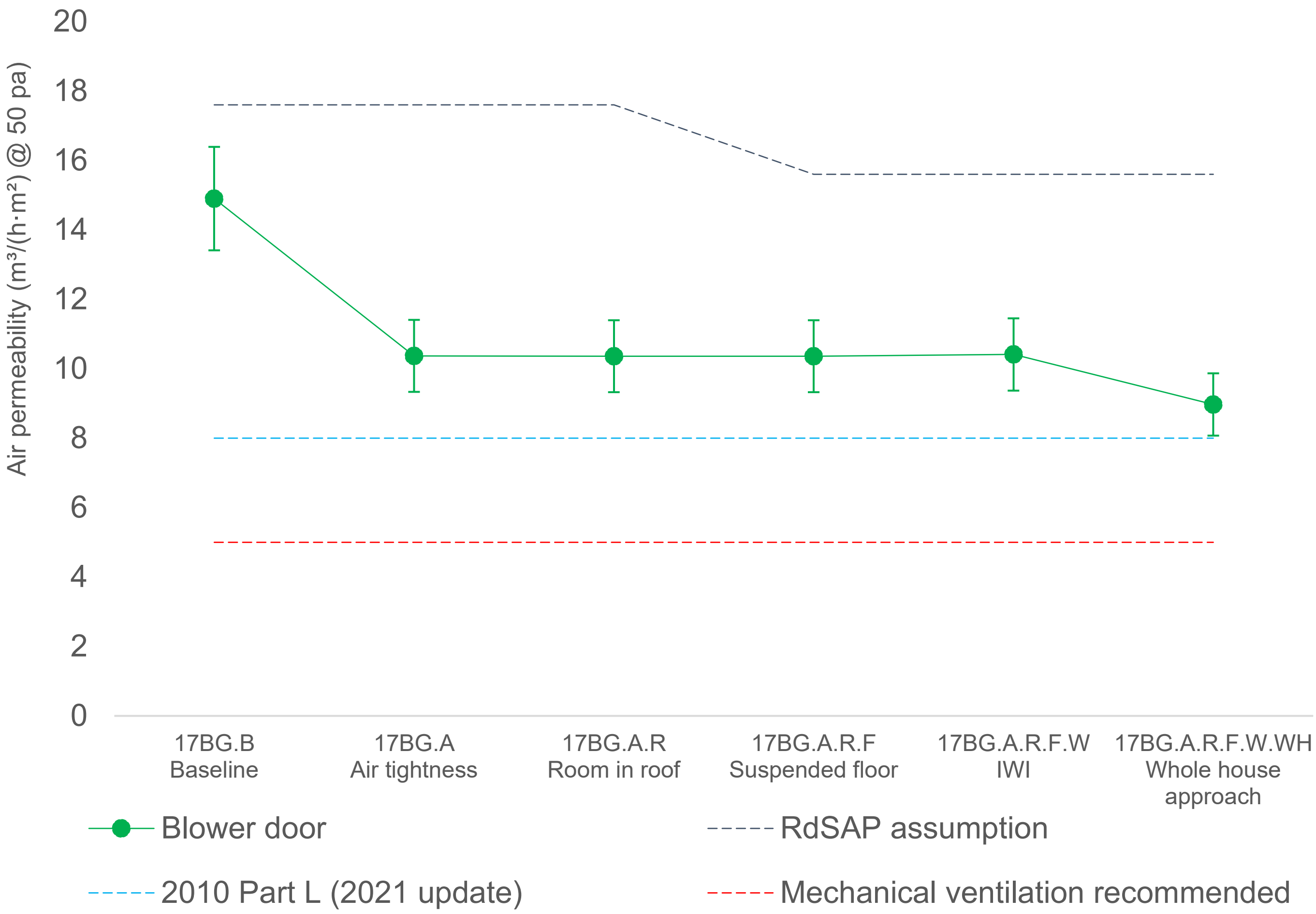

Figure 3-4 Airtightness improvements made at each retrofit stage

3.1.2 Sealing service penetrations can improve airtightness

Thermal imaging confirmed that the sealing of the penetrations using caulk successfully reduced direct air leakage in the kitchen and bathroom as shown in Figure 3-5. This is an interesting finding since it is a relatively simple activity to undertake and poor-quality sealing of penetrations are often visible, meaning airtightness testing and thermography may not be required to diagnose and address this.

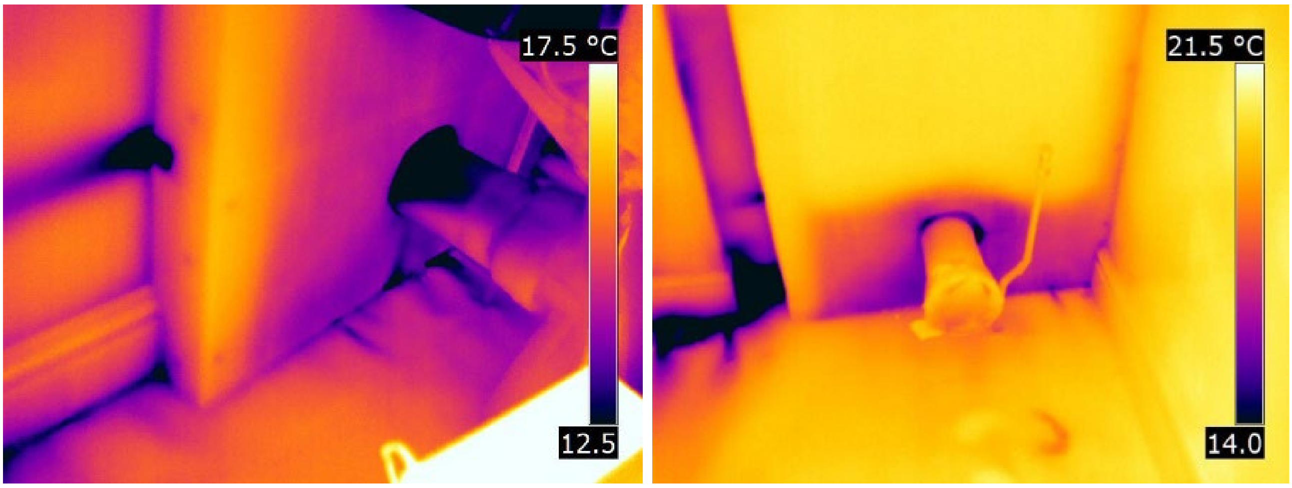

Figure 3-5 Air leakage before (left) and after (right) sealing penetrations

3.1.3 Sealing unused or surplus air bricks can improve airtightness

The covering up of air bricks, using sheets of PVC, may also have reduced air movement behind the IWI, reducing air leakage. However, it was not possible to capture this using thermography. Needless to say, if any purpose provided ventilation is to be removed in any naturally ventilated house a before and after airtightness test is essential to ensure that the property still has sufficient background ventilation post-retrofit. Although it cannot be quantified using thermography, it appears that sealing the air brick in the basement appeared to have also indirectly reduced infiltration via the ground floor to some degree;though it was not eliminated entirely. By monitoring the relative humidity in the basement, the basement air was found to be increasingly damp (RH < 80%). The basement air brick was therefore uncovered after the retrofit activities had completed to reduce further risk of damp, mould growth, and rot in suspended floor timbers.

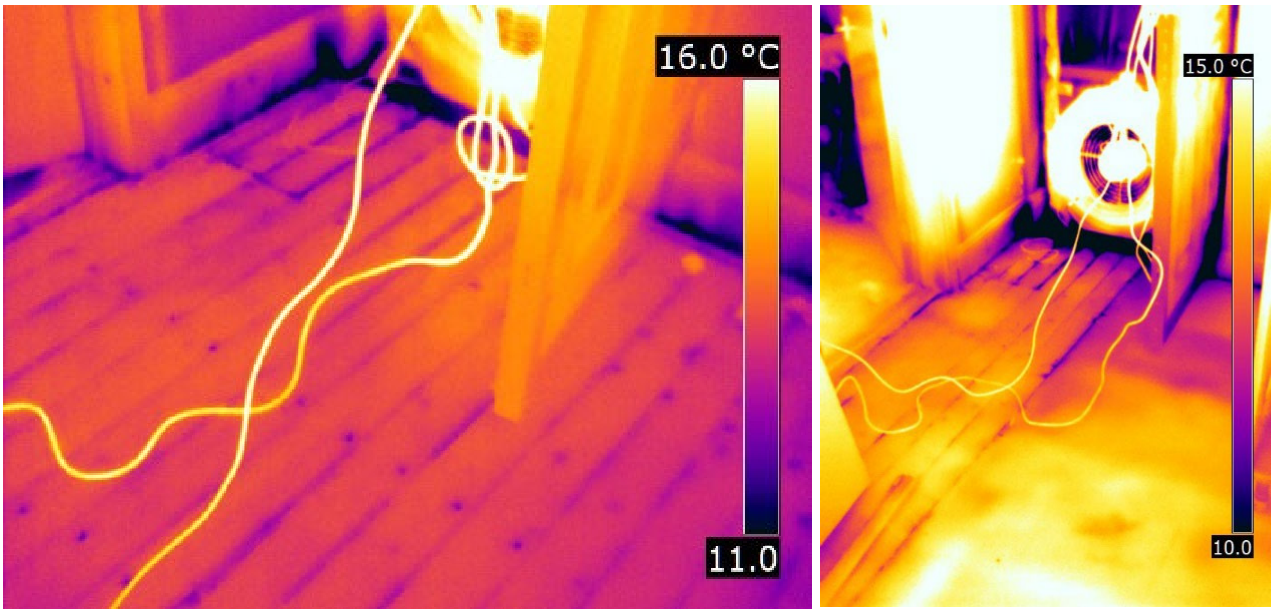

Figure 3-6 Air leakage through the suspended floor before (left) and after (right) sealing basement air bricks and floor retrofit

3.1.4 Installing insulation may not necessarily improve airtightness

As discussed, the initial airtightness improvements may have resulted in there being fewer incidental improvements resulting from the later floor, roof and wall retrofits. The lack of improvement in airtightness following the IWI retrofits is consistent with previous research findings [7] where installing IWI on wet plastered walls has not improved the baseline infiltration rates, though this may not be the case where walls are not wet plastered.

Airtightness reductions achieved via room-in-roof retrofits are less clear; the initial partial roof retrofit did not appear to make any airtightness improvements. However, the more extensive improvements made under the final whole house approach stage appear to have had some benefit; around a 16 % reduction, though the change is within the error of the test method. However, previous research has indicated that room-in-roof retrofits can reduce airtightness by around 11 % [8]. Thus, more research is needed on the potential for room-in-roof retrofits to reduce whole house infiltration rates.

The research also suggests that the floor retrofit failed to reduce infiltration, despite air leakage being observed around the ground floor. This is contrary to other research findings that have suggested that different floor insulation solutions, such as spray foam, can reduce infiltration by up to 40 % in homes with excessively high infiltration rates [9]. A seal to the floor perimeter was specified for the retrofit; however, it is not clear how successfully this was installed as site observations were restricted due to the COVID-19 pandemic lockdown, and photographic evidence was not obtained.

The potential for savings from floor insulation may therefore depend on the solution adopted (e.g. if vapour-open membranes are specified), quality of workmanship, and the degree of existing infiltration through the floor. In this case study, the mineral wool installed between joists in the suspended timber ground floor did not lead to airtightness improvements. Furthermore, the lack of reduction in infiltration may have been due to the basement ventilation having already been reduced in the initial airtightness retrofit stage, or due to there being limited through-ventilation in the floor void, since the home was a back-to-back construction. More research into suspended floor air exchanges is needed to fully understand this relationship.

3.1.5 Alternative measurements; low pressure Pulse tests and CO_2 decay tests

Two additional methods were also used to derive the air leakage in the dwelling, which were carried out at each retrofit stage.

Pulse tests were undertaken at 4 retrofit stages, yet on only one occasion did the test provide a valid result. This result of 2.12 $m^3/(h \cdot m^2)$ @ 4Pa came with a warning message that the achieved pressure range was too low. For all the invalid tests, the correlation coefficient (r^2) value was below the acceptable range. A combination of factors is believed to be the cause of the failed tests: in particular, an unstable suspended timber ground floor and acoustic (bounce-back) effects of pressurising buffer zones (the cellar and eaves knee walls), which discharge back to the habitable space at varying rates. When using the conversion factor quoted in CIBSE TM23 to convert a low-pressure Pulse test air tightness at 4 Pa to a 50 Pa value, the value was deemed to be 10.52 $m^3/(h \cdot m^2)$ @50pa, i.e. within the uncertainty of the blower door test value.

CO_2 tracer gas decay was measured several times at each retrofit stage. However, the analysis found the tests to be somewhat unreliable until after IWI retrofit had been completed in January 2021. Previous research has identified that success rates with using CO_2 tracer gas measurements to determine the air change rate of similar dwellings are low [10].

It was not possible to directly compare the data collected to validate the air changes identified by the blower door in this test dwelling since background CO_2 levels were highly variable and the ventilation rate was significantly affected by changing wind conditions (both average wind speeds and gustiness, and also with wind direction).

CO_2 decay measurements taken in January 2021 were based on a timed release of CO_2 on the ground floor of the house and concentrations recorded by sensors on the ground and second floors. The ground floor measurements showed air change rates ranging from 0.63 to 1.13 h^{-1} (mean 0.90 h^{-1}). The second-floor measurements displayed markedly lower air change rates of 0.24 to 0.60 h^{-1} (mean 0.38 h^{-1}), with the higher air change rates recorded during windier measurement periods.

Following each release, the time taken between the peak reading on the ground floor and the peak reading on the second floor ranged between 1½ and 2½ hours; generally the shorter time coincided with windier periods.

Airtightness improvement summary

The airtightness retrofit was successful in reducing the air permeability by around 40% from over 15 to around 9 $m^3/(h.m^2)$ @ 50Pa, on a par with new homes standards.

Most of this saving was achieved by sealing around service penetrations and closing off unused air bricks.

Insulating the ground floor and external walls had no measurable impact on airtightness, though insulation installed in the room-in-roof achieved some improvement.

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 are 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 and the contribution of fabric elements to HTC, as well as the predicted benefit achieved by retrofits.

A summary of the pre- and post-retrofit U-values for each of the fabric elements is presented in the following sections, from which some general observations can be made:

- The baseline pre-retrofit U-values were measured to be lower than default RdSAP assumptions, where there was thin internal wall insulation. This means that the baseline EPC score may be underestimated, and the benefit of additional insulation overestimated.
- The calculated U-values derived using the BRE calculator, based on observations of the construction were not always achieved by the U-values that were measured post-retrofit. This may be due to gaps in knowledge around the construction details, e.g. inconsistencies in the thickness of insulation installed, or presence of air movement between construction layers.
- The measured U-values did not often achieve the Approved Document Part L limiting U-values, since the thickness of insulation applied was limited. This was due to available space in the home, the thicknesses in which the product can be manufactured, or because of a reduced system thickness specified by the manufacturer.
- No insulation was added to the chimney breast to avoid losing additional internal floor space, or above the first floor ceiling to the eaves behind the room-in-roof knee walls since these were already insulated, so no change post-retrofit is recorded here.

3.2.1 Solid brick wall U-value improvements

As can be seen in Figure 3-7:

- Age defaults may overpredict external wall U-values if TIWI is installed; there is far greater correlation between measured and calculated U-values on uninsulated walls.
- RdSAP age bands and calculated U-values may not be providing realistic U-values if chimneys are sealed. This can be significant in small homes where chimneys make up a large proportion of the external wall area.
- Otherwise, calculated U-values tend to provide good agreement with measured data.
- The post-retrofit U-values were similar regardless of which method was used to derive the U-values.

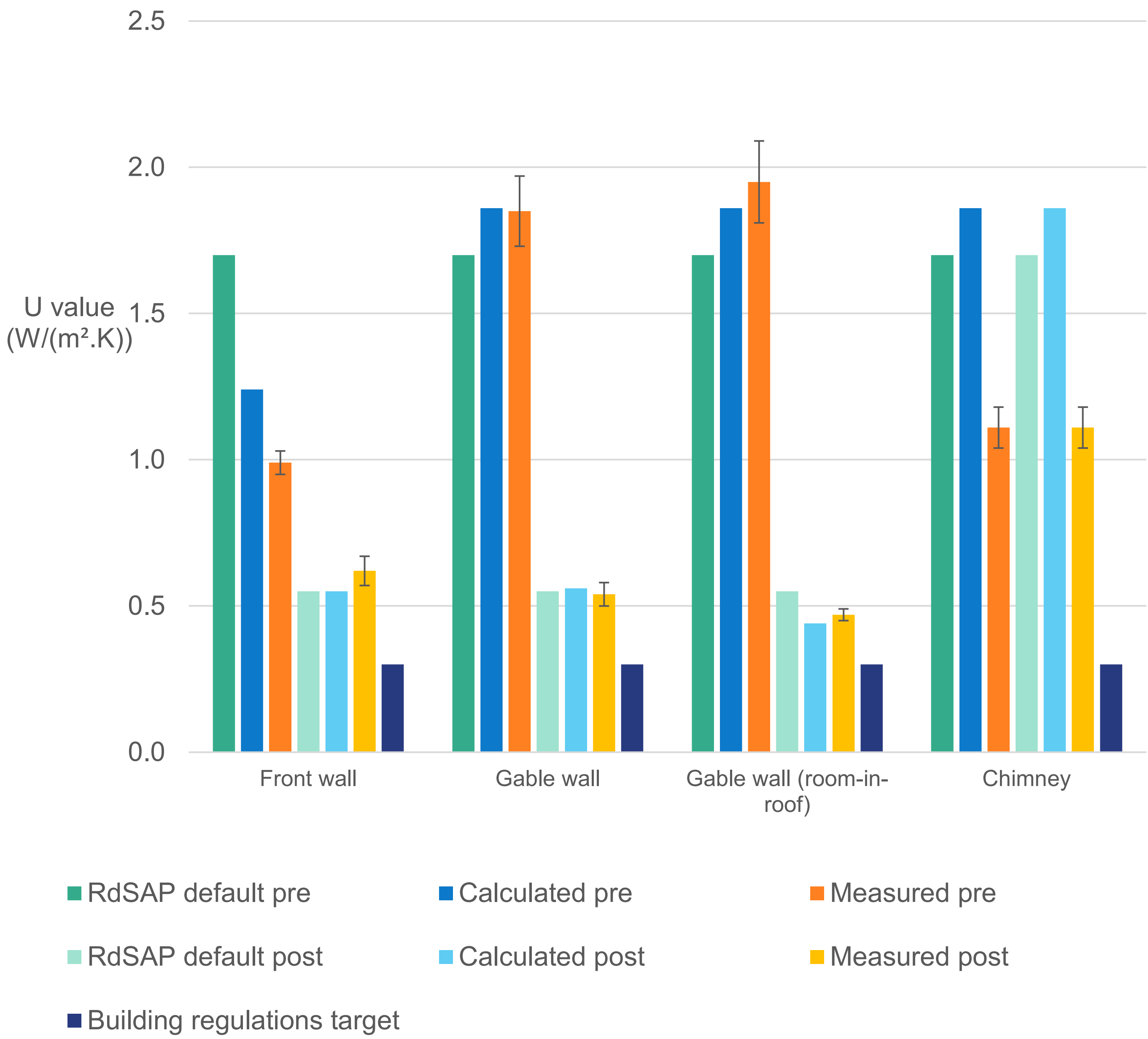

Figure 3-7 Pre- and post-retrofit wall U-values

3.2.2 Suspended timber ground floor U-value improvements

As can be seen in Figure 3-8:

- The pre-retrofit age band suspended timber ground floor U-value estimates were relatively similar to the calculated and measured U-values in the living room.
- However, in the kitchen, where there was a basement below, the measured U-value was almost twice that of the RdSAP age bands and calculated U-values.
- The post-retrofit U-value estimates were all similar, regardless of which method was used to derive them.

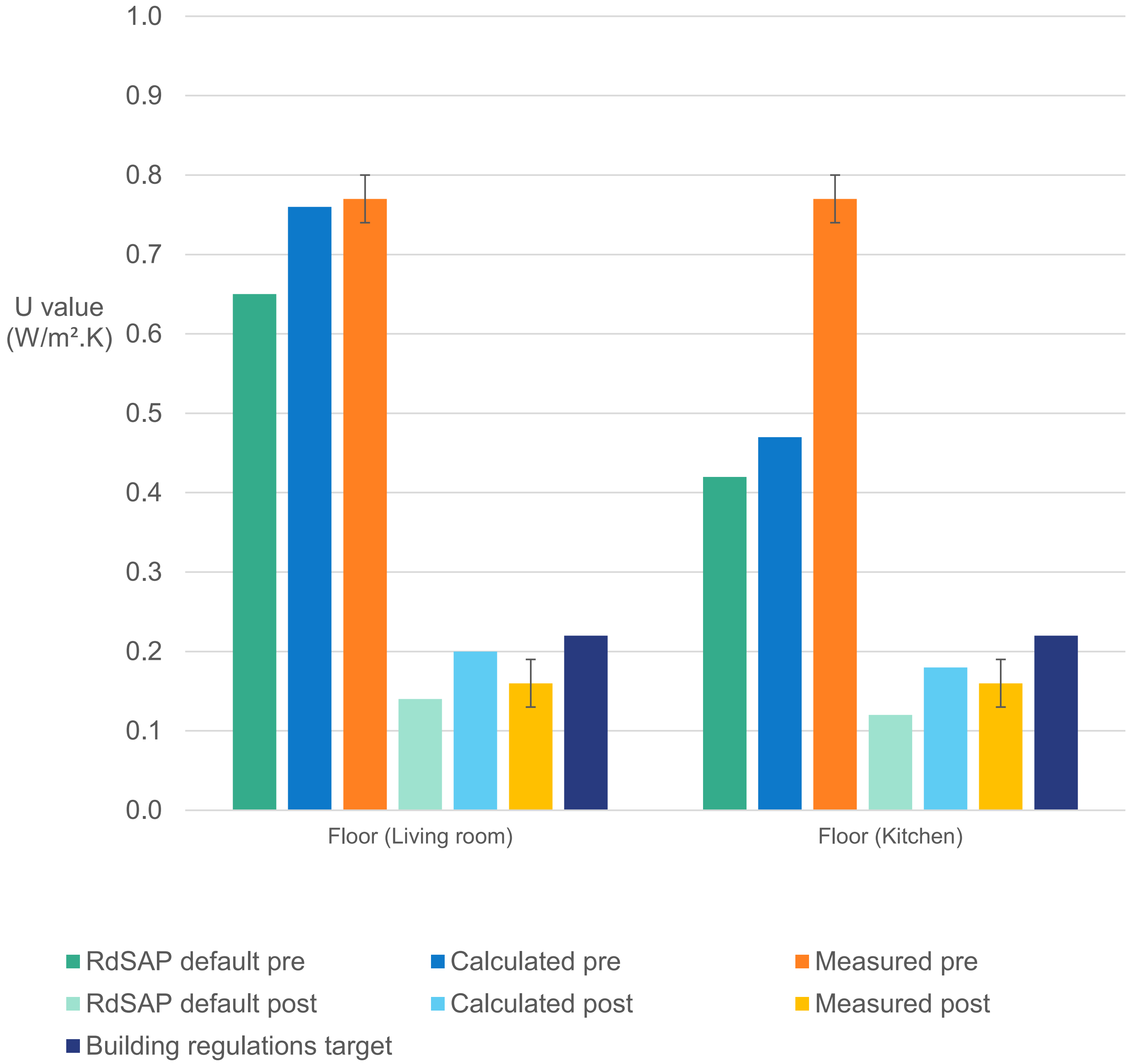

Figure 3-8 Pre- and post-suspended timber ground floor U-values

3.2.3 Room-in-roof U-value improvements

As can be seen in Figure 3-9:

- The pre-retrofit age band estimates for sloping roof, dormer cheek, and dormer walls substantially overpredict U-values
- The post-retrofit U-value estimates were all similar, regardless of which method was used to derive the U-values.
- RdSAP age band defaults for insulated and uninsulated lofts are relatively similar to the calculated and measured values.

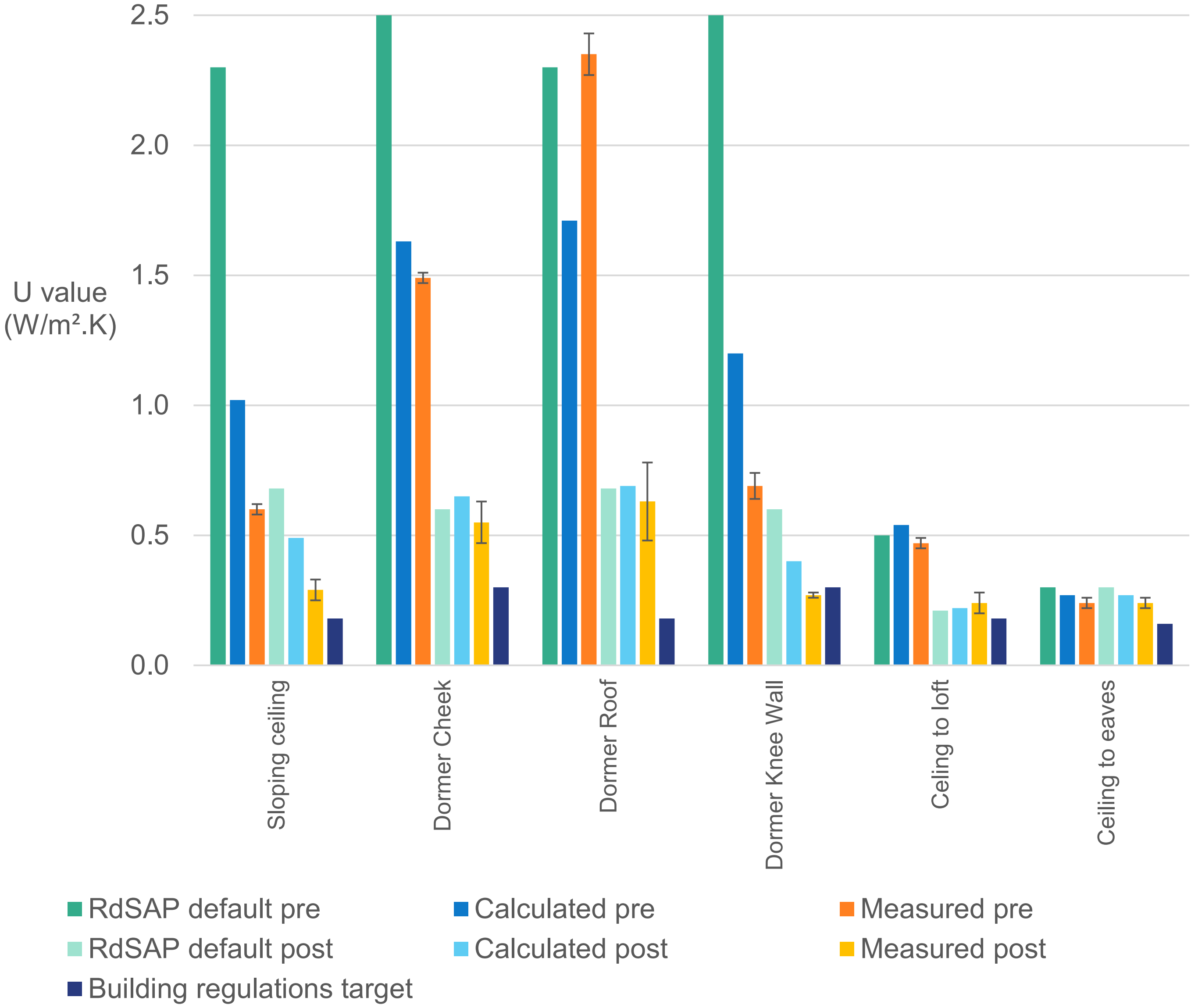

Figure 3-9 Pre- and post-retrofit room-in-roof U-values

While some of the retrofit measures did not achieve the expected reduction in the U-values, the differences were minor. Since we were not always able to ascertain the original construction of building materials, the calculated the U-values used some assumptions about the construction. Additionally, since the installation was not observed, it is not known if installation errors took place which may also account for any minor discrepancies.

As seen in Table 3-1, substantial reductions in U-values were measured because of the retrofit, although the default values, the calculated U-values, and measured U-values were often not in alignment. This indicates the extent of the performance gap and the degree to which models could be made more accurate if default U-value data is updated.

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

	Pre retrofit			Post retrofit		
	RdSAP Default	Calculated	Measured	RdSAP Default	Calculated	Measured
External wall (front)	1.70	1.24	0.99 ± 0.04	0.55	0.55	0.62 ± 0.05
External wall (gable)	1.70	1.86	1.85 ± 0.12	0.55	0.56	0.54 ± 0.04
External wall (gable RIR)	1.70	1.86	1.95 ± 0.14	0.55	0.44	0.47 ± 0.02
Chimney walls	1.70	1.86	1.11 ± 0.07	1.70	1.86	1.11 ± 0.07
Suspended timber floor (Living room)	0.67	0.76	0.77 ± 0.03	0.18	0.20	0.16 ± 0.03
Suspended timber floor (Kitchen)	0.67	0.47	0.77 ± 0.03	0.16	0.18	0.16 ± 0.03
Sloping ceiling	0.77	1.02	0.60 ± 0.02	0.56	0.49	0.29 ± 0.04
Dormer cheek	2.30	1.63	1.49 ± 0.02	1.23	0.65	0.55 ± 0.08
Dormer roof	2.30	1.71	2.35 ± 0.08	0.90	0.81	0.63 ± 0.15
Dormer knee wall	2.30	1.20	0.69 ± 0.05	0.59	0.40	0.27 ± 0.01
Loft	0.50	0.54	0.47 ± 0.02	0.23	0.22	0.24 ± 0.04
Ceiling to eaves	0.40	0.27	0.24 ± 0.02	0.40	0.27	0.24 ± 0.02

The percentage improvements in U-values achieved for each element are listed in Table 3-2 for each approach to acquiring U-values. Applying insulation resulted in substantial improvements to the U-values, up to 75 % for the uninsulated walls, with the largest improvement observed at the suspended floor, then the dormer roof and uninsulated external walls.

It is also interesting to note that the reduction achieved depends on the method of acquiring the data. The implication of this is that without measured data there may be an unknown difference in the savings predicted versus those achieved, which will vary based upon the data collection method. This is explored further in Table 3-2 which also shows the potential performance gap and prediction gaps (when using RdSAP) that occur in the fabric retrofits, specifically:

RdSAP defaults prediction gap = difference between the RdSAP defaults for post-retrofit U-values vs measured post-retrofit U-values

Performance gap = difference between ‘as built’ calculated post-retrofit U-values vs measured post-retrofit U-values

Table 3-2 Summary of measured U-value reductions and gaps in performance

Element	RdSAP default predicted reduction (W/(m²·K))	Calculated predicted reduction (W/(m²·K))	Measured reduction (W/(m²·K))	RdSAP defaults prediction gap%	“as built” performance gap%
External wall (front)	1.15	0.69	0.37	13%	13%
External wall (gable)	1.15	1.30	1.31	-2%	-4%
External wall (gable RIR)	1.15	1.42	1.48	-15%	7%
Suspended timber floor (living room)	0.49	0.56	0.61	-11%	-20%
Suspended timber floor (kitchen)	0.51	0.29	0.61	0%	-11%
Sloping ceiling	0.21	0.53	0.31	-48%	-41%
Dormer cheek	1.07	0.98	0.94	-55%	-15%
Dormer roof	1.40	0.90	1.72	-30%	-22%
Dormer knee wall	1.71	0.80	0.42	-54%	-33%
Loft	0.27	0.32	0.23	4%	9%

This analysis confirms that the prediction gap can be substantial when RdSAP default data is used and tends to be larger than the performance gap observed between the measured and the calculated values that are expected.

This has substantial implications when predicating retrofit savings. Although most of the external wall was uninsulated, there had previously been some thin IWI (TIWI) installed on the front external wall. This consisted of 20 mm polystyrene-backed plasterboard. It is not known if this was part of a previous retrofit strategy by the landlord, nor why only the front wall was treated. However, the TIWI reduced the U-value of the wall by half, compared to the uninsulated walls. Several further observations on the U-value reductions can be made:

- Dormer roofs and cheeks can be poorly performing and will benefit from insulation.
- Chimneys can be left uninsulated during IWI retrofits, owing to concerns around losing too much floor area. Additionally, they have lower U-values than external walls, since they act as an unheated sheltered space. Little work has been undertaken to understand heat loss through chimneys before and after IWI retrofits.
- Often the same fabric elements in the house will have different U-values where different levels of insulation have been applied heterogeneously (e.g. 17BG's external walls and lofts (ceiling) had different U-values), complicating the data input for EPC assessors.
- Ease of installation affects the likelihood of elements being insulated. For example, the two areas of loft had different thermal performance: the accessible loft behind the knee walls (first floor ceiling) was well insulated, the inaccessible loft was poorly insulated.

Some external walls in 17BG had thin (≈ 20 mm) IWI installed before the retrofit began, which resulted in the U-value of the pre-retrofit wall being measured to be half that of the other external walls without the thin IWI pre retrofit. However, the minimum insulation thickness that can be applied in RdSAP is 50 mm; insulation below this thickness is ignored in the model, thus the RdSAP pre-retrofit model under predicted the energy efficiency of the house.

This omission means the house may have been given too low an EPC rating and any retrofit savings predicted by the model may be overestimated. It is not uncommon for homes to have had thin amounts of insulation added to walls when replastering has taken place and this therefore represents an area of inaccuracy in EPCs, which could be addressed relatively simply by reducing the iterative insulation thickness that can be included in RdSAP software (e.g. at 10 mm or 20 mm increments).

3.2.4 Contribution of individual elements to fabric heat loss (HTC_f)

Figure 3-10 shows what impact the improvement in U-values may have had on fabric heat loss, when considering the U-values coupled with the relative size of heat loss area of each element in order to to illustrate the implications of using default RdSAP, calculated, or measured U-value inputs:

- HTC_f is highest when RdSAP defaults are used, and lowest when measured U-values are used in this case study dwelling, since some thin insulation was present before the retrofit.
- The gap between HTC_f using defaults, calculated, and measured U-values becomes smaller post retrofit.
- Walls are the most significant element, responsible for around 60 % of HTC_f pre- and post-retrofit.
- Share of HTC_f from windows and doors (which were not replaced) doubles post-retrofit to over 15 %.

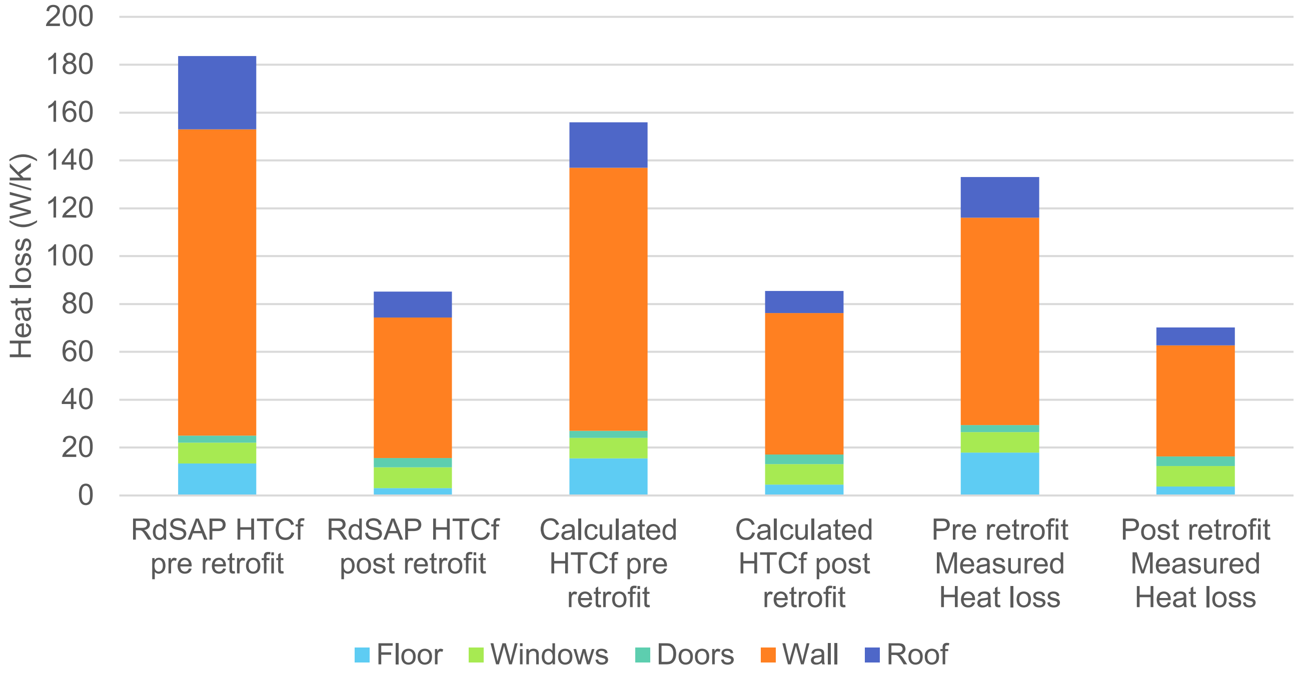

Figure 3-10 Heat transfer coefficient of fabric elements (HTC_f) pre- and post-retrofit, as recorded by heat flux density measurements

U-value improvement summary

The retrofits achieved substantial reductions in fabric heat losses, almost halving the associated heat loss. They achieved U-value reductions between 37 % (where there were already some levels of thin pre-existing insulation) and 79% , where the fabric was uninsulated.

The assumed age band-related RdSAP default U-values were generally overestimated, when compared with calculated and measured values, and may need reviewing.

The walls make up the largest heat loss of all the fabric elements both pre- and post-retrofit.

3.3 Whole house heat loss (HTC) improvement

The total measured heat loss for the dwelling at each stage is shown in Table 3-3. The cumulative benefit of each retrofit has reduced the HTC by around a half. Those interventions that had the highest impact were the airtightness improvements, the IWI and room-in-roof retrofits. However, the uncertainty associated with the 17BG.A test makes it difficult to determine which had the most benefit. Conversely, the suspended timber floor retrofit had no measurable improvement. The potential HTC reductions from floor retrofits warrants further investigation.

17BG is a back-to-back home and therefore has a large area of party wall relative to the heat loss area. Although fairly common, this limits the potential to achieve more accurate measurements, since party wall heat loss is an area of uncertainty when calculating the HTC. This uncertainty limits the accuracy of the measured reductions in heat loss achieved by minor retrofits.

Table 3-3 Test house HTC after each retrofit stage

Retrofit stage	HTC (W/K)	HTC Uncertainty	HTC Reduction (W/K)	% reduction
17BG.B Base case	197 ± 6	3%	n/a	n/a
17BG.A Airtightness improvement	144 ± 26	18%	53 ± 27	(27 ± 14)%
17BG.A.R Room-in-roof insulation	131 ± 7	5%	13 ± 27	(9 ± 19)%
17BG.A.R.F Suspended timber ground floor insulation	134 ± 8	6%	-3 ± 11	(-2 ± 8)%
17BG.A.R.F.W Internal wall insulation	109 ± 9	8%	25 ± 12	(19 ± 9)%
17BG.A.R.F.W.WH Whole house approach measures *(removing discontinuities in IWI and RIR retrofits)*	106 ± 5	5%	3 ± 10	(3 ± 9)%
Cumulative reduction			***98 ± 14***	***(46 ± 4)%***

In most instances, there was a relatively small uncertainty associated with the coheating test (2 to 9%), except for the 17BG.A (airtightness retrofit) test, which had double the rate of uncertainty compared to the next highest at 18%. Factors that may have contributed to the high uncertainty are linked to the test conditions during this period: 1) high levels of solar gain during this test (March 2020), and 2) failure in party wall heat flux density measurements (only three out of nine HFPs recorded data).

Savings to and from 17BG.A are, therefore, made with caution and this highlights the importance of capturing party wall heat flux density on every party wall during coheating tests. The improvements achieved by each retrofit stage are in Figure 3-11, showing the coheating test results used in the analysis to evaluate the success of the retrofits.

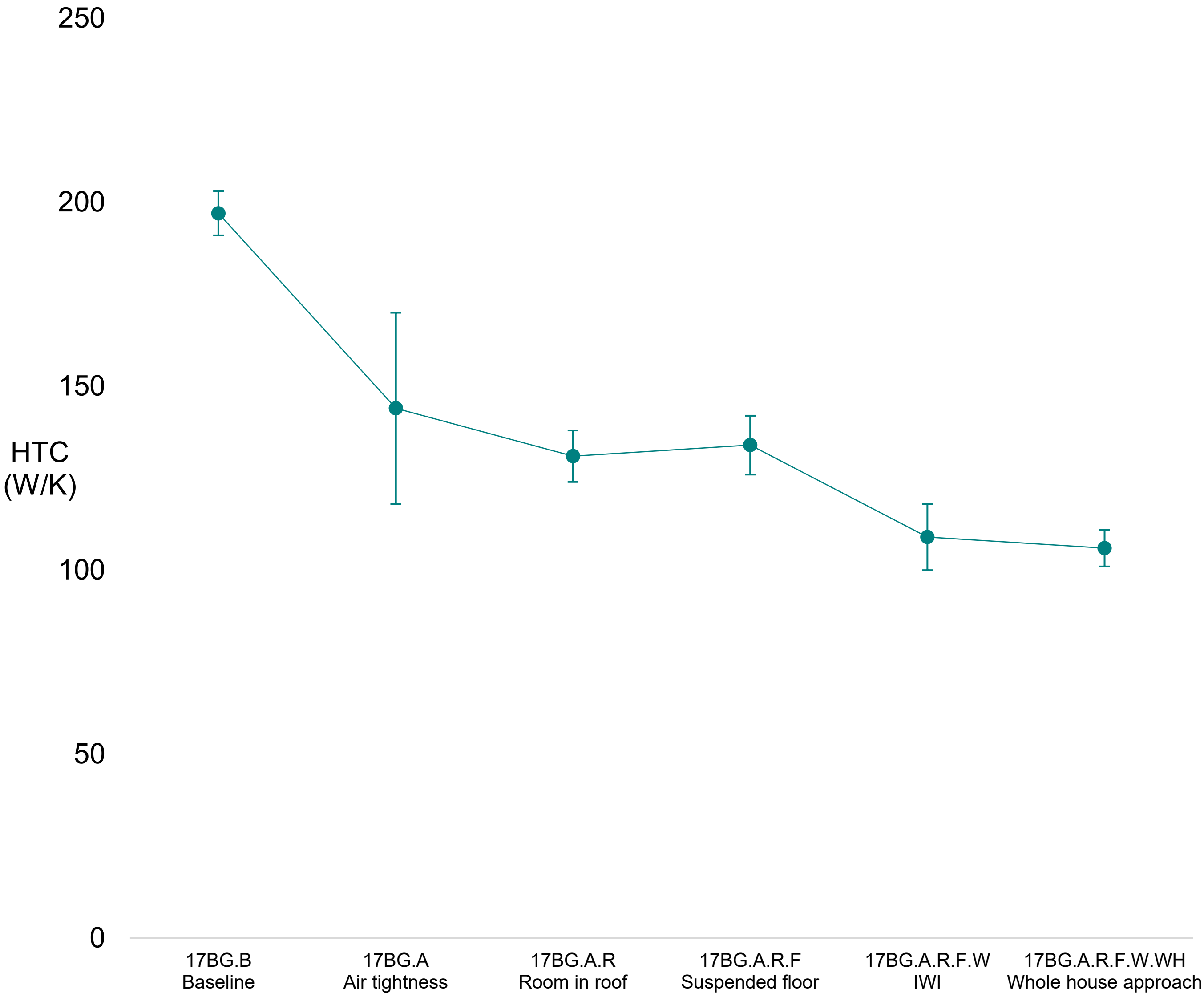

Figure 3-11 Coheating HTC at each retrofit stage

The whole house retrofit at 17BG has been successful in reducing HTC by half, although there is some uncertainty around the contribution of each retrofit measure. The following sections discuss the reductions in more detail.

3.3.1 Infiltration heat loss reductions (HTC_v) 17BG.A

The greatest reduction by a single retrofit appears to have been achieved by reducing the airtightness of the dwelling – yielding a (53 ± 27) W/K, or (27 ± 14) %, reduction. However, the uncertainty associated with the 17BG.A test was larger than normal, thus, the saving may be overestimated. However, the dwelling had particularly poor airtightness to begin with, so it is reasonable to expect that addressing this resulted in a meaningful reduction in the HTC of the dwelling. Based on the literature, more substantive fabric retrofits like solid wall insulation have been shown to achieve between 13 % and 68 % HTC [4, 7, 11].

As a check on the measured HTC results, an alternative approach to estimate the heat loss attributable to the airtightness improvements, using only the blower door results and the n/20 'rule of thumb' can be used.

When considered as a heat loss, the background infiltration of the baseline house, prior to any retrofits taking place, was estimated to be 38 W/K according to Equation 1.

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

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

According to this method the HTC saving achieved from airtightness improvements would be over 11 W/K.

As already discussed, the HTC reduction due to the airtightness improvements measured by the coheating test was substantially higher: (53 ± 27) W/K. It may be that this mean value is overestimated, indeed, this is higher than the total estimated HTC_v in the DSM models. There may be several reasons for this, including:

1) Substantial uncertainty in the coheating tests undertaken
2) Uncertainty around the influence of large party wall heat losses
3) Changes in infiltration characteristics
4) The n/20 rule of thumb may need adapting for different dwelling forms

HTC_v calculations assume that infiltrating air is entering at external temperature, yet in houses such as 17BG much of the infiltrating air originates from the basement beneath. Although not directly heated, the basement did gain some heat from the rooms above, providing some pre-conditioning, and as the airtightness retrofit effectively reduced air leakage through external wall penetrations, the characteristics of the infiltrating air may have been altered.

More research to investigate the n/20 rule of thumb is therefore needed, and any attempt to disaggregate whole house HTC into fabric and ventilation heat loss, using n/20 should be treated with caution. This has been demonstrated in a recent publication, where this rule of thumb is shown to be inappropriate for a sample set of 21 buildings [12]. Investigation using a larger sample set would be required to identify an alternative rule of thumb for UK archetypes.

3.3.2 Room-in-roof (RIR) heat losses 17BG.A.R

The RIR retrofit was measured to reduce HTC by (13 ± 27) W/K, or (9 ± 19) %. Such a large saving may be due to the room-in-roof making up 30 % of the home's heat loss area. The relatively high uncertainty in the savings is again due to the uncertainty in the 17BG.A test. Therefore, it may not be possible to apportion the savings between airtightness and room-in-roof improvements with a high degree of confidence. There were much lower estimates of uncertainty when comparing the cumulative benefit of the RIR and airtightness retrofits together, i.e. between the baseline (17BG.B) and post-retrofit RIR tests (17BG.A.R). This means that there is a greater level of confidence in the cumulative savings of the airtightness and room-in-roof retrofit combined. The effect of both measures was to reduce the HTC by (66 ± 10) W/K.

However, this RIR retrofit may only be considered as a *partial* RIR retrofit, since it was assumed by the installer that adequate insulation was already installed on the sloping ceiling, the loft, and the dormer roof. On investigation post-retrofit, it was observed not to be the case. This is an illustration of the complexity of retrofit specifications in homes where the characteristics of the existing fabric are difficult to discern.

Thus, in this stage, only the knee walls were insulated, with 75 mm XPS between the existing batons, as shown in Figure 3-12. The gable wall was fitted with 72 mm of wood fibre board IWI (including in the intermediate floor void), as shown in Figure 3-13, and mineral wool was also installed on the dormer cheeks, as shown in Figure 3-14. The sloping roof and flat ceiling to the loft were eventually insulated (in the final whole house approach stage) when it was identified that they were not adequately insulated.

Figure 3-12 Knee wall insulation mid-retrofit (17BG.A.R)

Figure 3-13 Gable wall insulation mid-retrofit (17BG.A.R)

Figure 3-14 Dormer cheek insulation mid-retrofit (17BG.A.R)

3.3.3 Suspended timber ground floor heat losses 17BG.A.R.F

The floor retrofit at 17BG involved 200 mm of mineral wool being fitted between joists under the floorboards, as shown in Figure 3-15. As there was a half-basement, only half the floorboards needed to be removed and replaced. In doing so, however, the floorboards were damaged and needed to be replaced by a new floor. An air membrane was specified to reduce air leakage, though site observations were limited during the Covid pandemic, and so it was not possible to confirm if this was installed successfully. It is recommended, but not always undertaken in homes, so this may reflect common installation practice for suspended floor retrofits.

Figure 3-15 Suspended timber ground floor insulation mid-retrofit (17BG.A.R.F)

Despite the addition of insulation, and a substantial improvement in the U-value being achieved, no improvement in HTC was measured following the retrofit. The post-retrofit coheating test result was a marginal increase of (3 ± 11) W/K, or (2 ± 8) %, i.e. no measurable change was detected.

The lack of measurable improvement may have been due to various factors. The floor area contributed only a relatively small proportion of the total dwelling heat loss area, only 23.3 m^2 out of a total dwelling heat loss area of 128.6 m^2. Following airtightness improvements, a high proportion of air infiltrating into the house originated from the cellar and increasing the thermal resistance of the ground floor may have reduced the temperature of this infiltrating air. There was also a specific issue with the environmental conditions during the test: on closer examination of the data, a thermostat sensor in the bathroom was observed to have erroneously maintained the heating to 24 °C in this floor retrofit stage, rather than 23 °C used elsewhere. The bathroom is a small contribution to the overall house volume; however, it may have resulted in additional increases in energy consumption and heat loss during the test, which will have made the resultant HTC higher.

3.3.4 External wall heat losses 17BG.A.R.F.W

Following the floor retrofit, the walls were internally insulated, with 52 mm of wood fibre board, as shown in Figure 3-16.

Figure 3-16 IWI mid-retrofit (17BG.A.R.F.W)

The IWI was only a partial retrofit, since the room-in-roof gable wall had already been insulated as part of 17B.A.R. Additionally, no new IWI was added to the kitchen wall, to replicate a room-by-room retrofit. Half the bathroom wall, around the boiler and WC, was also left uninsulated to investigate the implications of leaving difficult-to-access locations uninsulated.

Despite these omissions, the IWI still resulted in the second largest saving of (25 ±12) W/K in HTC or a (19 ± 9) % reduction. This is a substantial saving, and, as mentioned, it is an underestimate of the true potential of IWI because of the areas omitted from the retrofit.

3.3.5 Whole house approach 17BG.A.R.F.W.WH

This final stage has been included to evaluate the performance implications and unintended consequences of omissions that can occur during piecemeal retrofits. As listed in Table 1-3 for 17BG, these were as follows:

- IWI kitchen and bathrooms (common approach to landlord property maintenance) Figure 3-17
- Insulate RIR loft (contractor assumed insulated previously and no loft hatch to access) Figure 3-18
- RIR sloping ceiling, dormer roof & cheek insulation (contractor assumed insulated); Figure 3-19

Figure 3-17 Comparing IWI bathroom discontinuity in 17BG.W (left) and complete IWI (17BG.A.R.F.W.WH) (right)

Figure 3-18 Ceiling removal to access loft to install insulation and replacement mid-installation (17BG.A.R.F.W.WH)

Figure 3-19 Dormer roof, cheeks and sloping ceiling insulation retrofit stages (17BG.A.R.F.W.WH)

Despite the extensive works, the cumulative impact of these on energy performance was measured to be marginal. Adding these only reduced the whole house HTC by (3 ±10) W/K, or

(3 ± 9) %, i.e. not statistically significant. One reason, as mentioned, could be that the bathroom and kitchen walls had already had TIWI, meaning the IWI made smaller improvements to U-values than when installed on uninsulated walls.

In improving the quality of the fabric during this final whole house approach stage, particularly in the room-in-roof, an incidental improvement in airtightness from 10.9 to 9.2 $m^3/(h.m^2)$ @50Pa was achieved. Applying the n/20 rule of thumb to this, suggests that there may have been a 4 W/K ventilation heat loss reduction following the room-in-roof insulation (17BG.A) according to Equation 1. However, the fabric improvements made in this stage were substantial, and it is unknown how reliable this rule of thumb is for different house types and fabric performance levels. More research is required to understand estimates based on this rule.

The HTC reductions for the whole house approach specific measures were marginal, thus it is important to understand the role of these measures in reducing risks of retrofits.

The cumulative benefit of all the retrofits combined is more certain: the HTC was reduced from a baseline of (197 ± 6) W/K, to (106 ± 5) W/K. This is a substantial reduction of (91 ± 8) W/K, or (46 ± 4) %, which illustrates how effective whole house retrofits can be at reducing heat loss from homes. The cumulative savings achieved by each of the retrofit stages are shown in Figure 3-20.

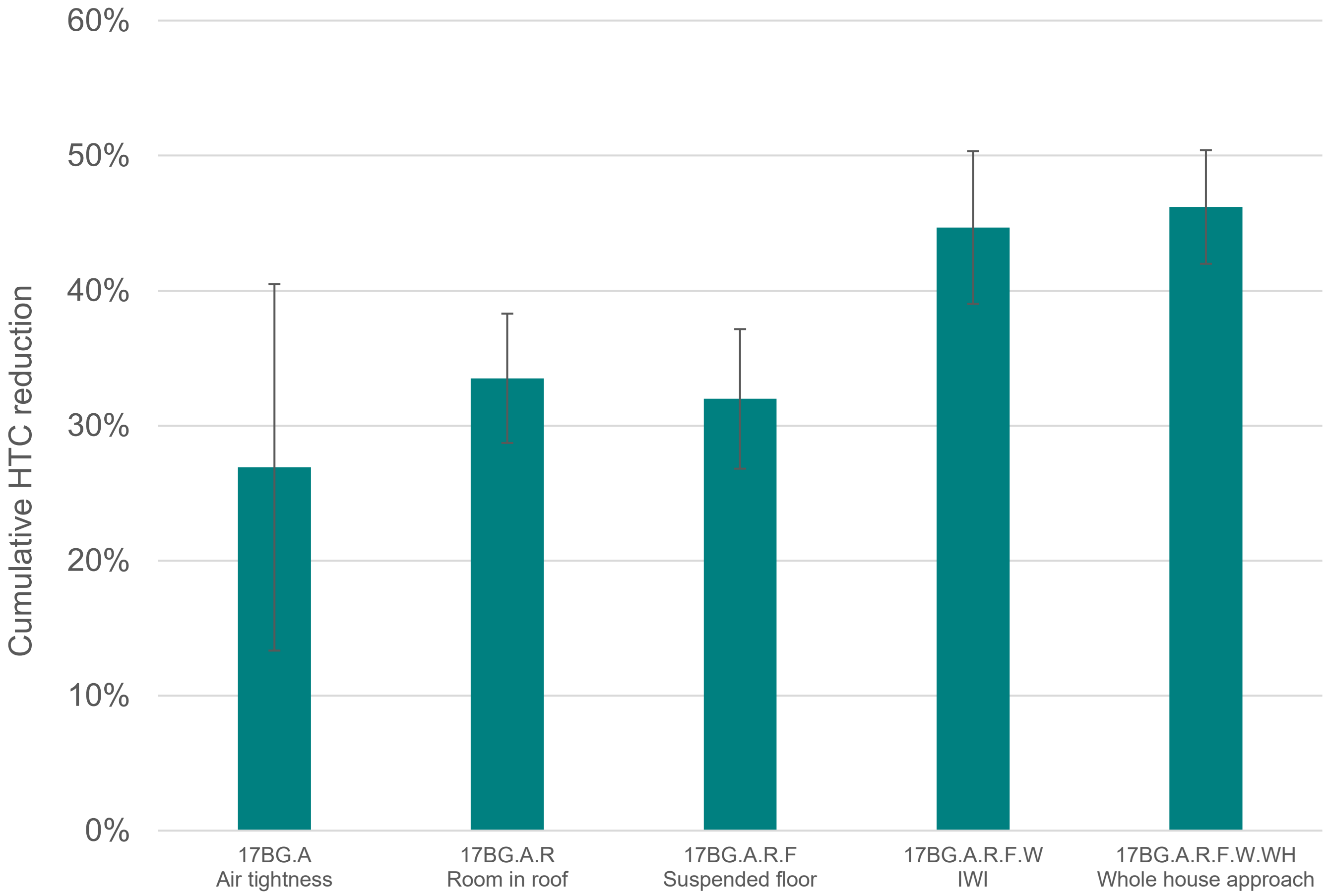

Figure 3-20 Cumulative HTC savings achieved by retrofits

3.3.6 QUB and the coheating test HTC results

An alternative method of measuring the HTC is QUB (as described in the DEEP Methods 2.0 Report). It was undertaken in the home at different retrofit stages to compare against the coheating test. In total, 22 QUB tests were performed on 17BG at four stages: baseline; after the RIR retrofit; after the IWI retrofit; and after the final whole house approach measures were installed.

This was done to investigate the reliability and accuracy of the QUB test. Out of these, six tests were discounted based on the test α-value (a ratio of power input, temperature difference, and the HTC of the property) being outside of recommended limits. This was a result of the QUB tests being completed immediately following the coheating test, resulting in significant changes in internal temperature between tests. Each test was of 10 hours duration. The tests were completed in February 2020 (baseline), October 2020 (room-in-roof), January 2021 (IWI), and March 2021 (whole house approach).

The results of the remaining 16 tests are shown in Figure 3-21, compared against the upper and lower uncertainty limits of the measured coheating HTC (with no adjustments made for party wall losses), which are represented through dotted lines. Despite the property being a back-to-back end-terrace with party walls, no heat flux density measurements were taken throughout the QUB tests, so comparison against the HTC adjusted for party wall losses cannot be made.

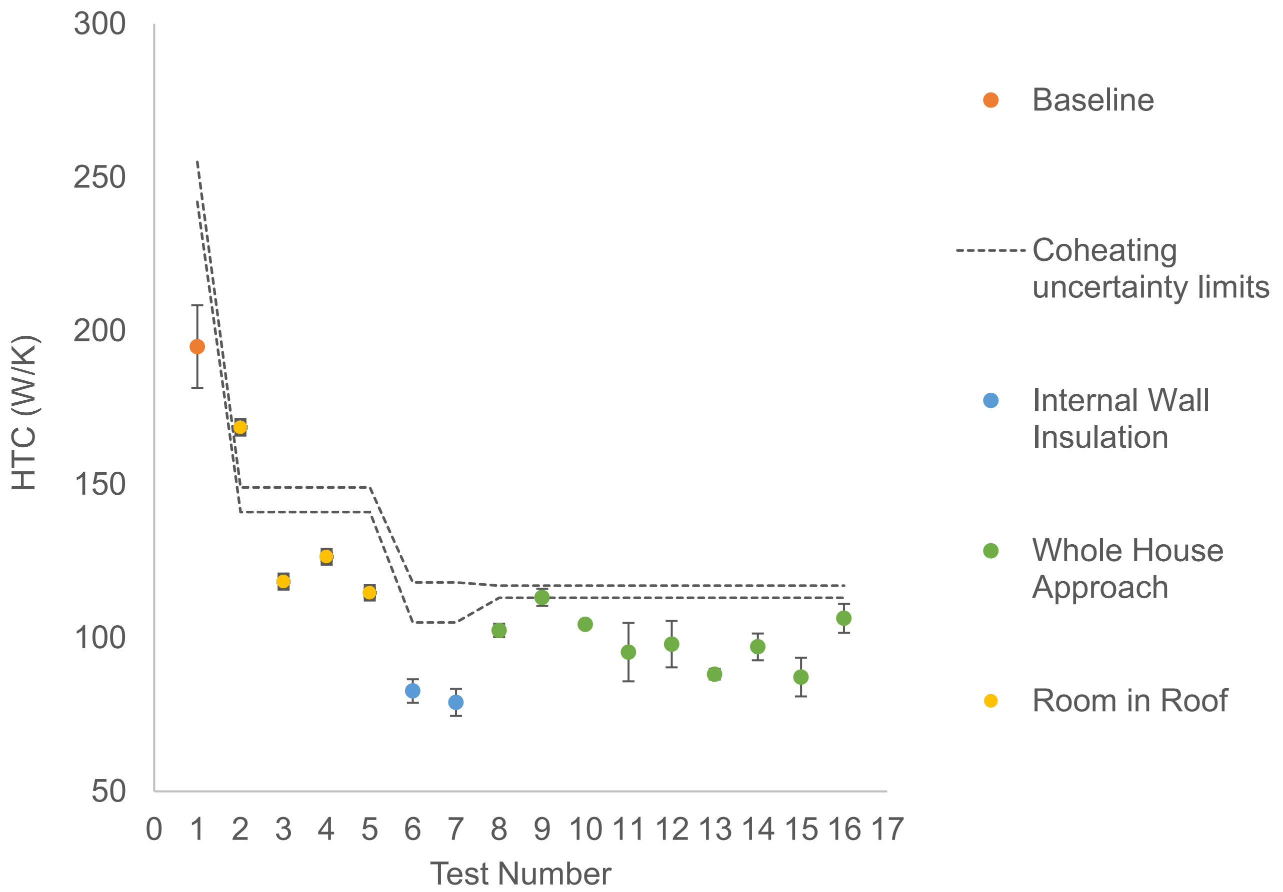

Figure 3-21 Predicted HTC via QUB test

All the QUB estimates are lower than the coheating HTC values, and all but two of the 16 tests are outside the uncertainty boundaries of the coheating HTC. There is also noticeable variation in repeated tests for the same configurations.

The uncertainty weighted average of the four stages where QUB tests were completed are shown in Figure 3-22. As with the individual tests, these average values are less than the corresponding HTC measured through coheating, although the uncertainty boundaries overlap for two configurations. When comparing the HTC improvement detected between baseline and hhole House approach stages, a 48 % improvement is recorded for QUB and a 54 % for coheating (no party wall adjustment).

The cause of this is not yet determined. A possible reason is differing heat flow patterns through elements that do not face the external environment, such as party walls and basements, for the two measurement procedures. Heat flows to such spaces contribute to the HTC, but the temperatures in these spaces were not monitored throughout the QUB tests, so cannot be analysed in detail.

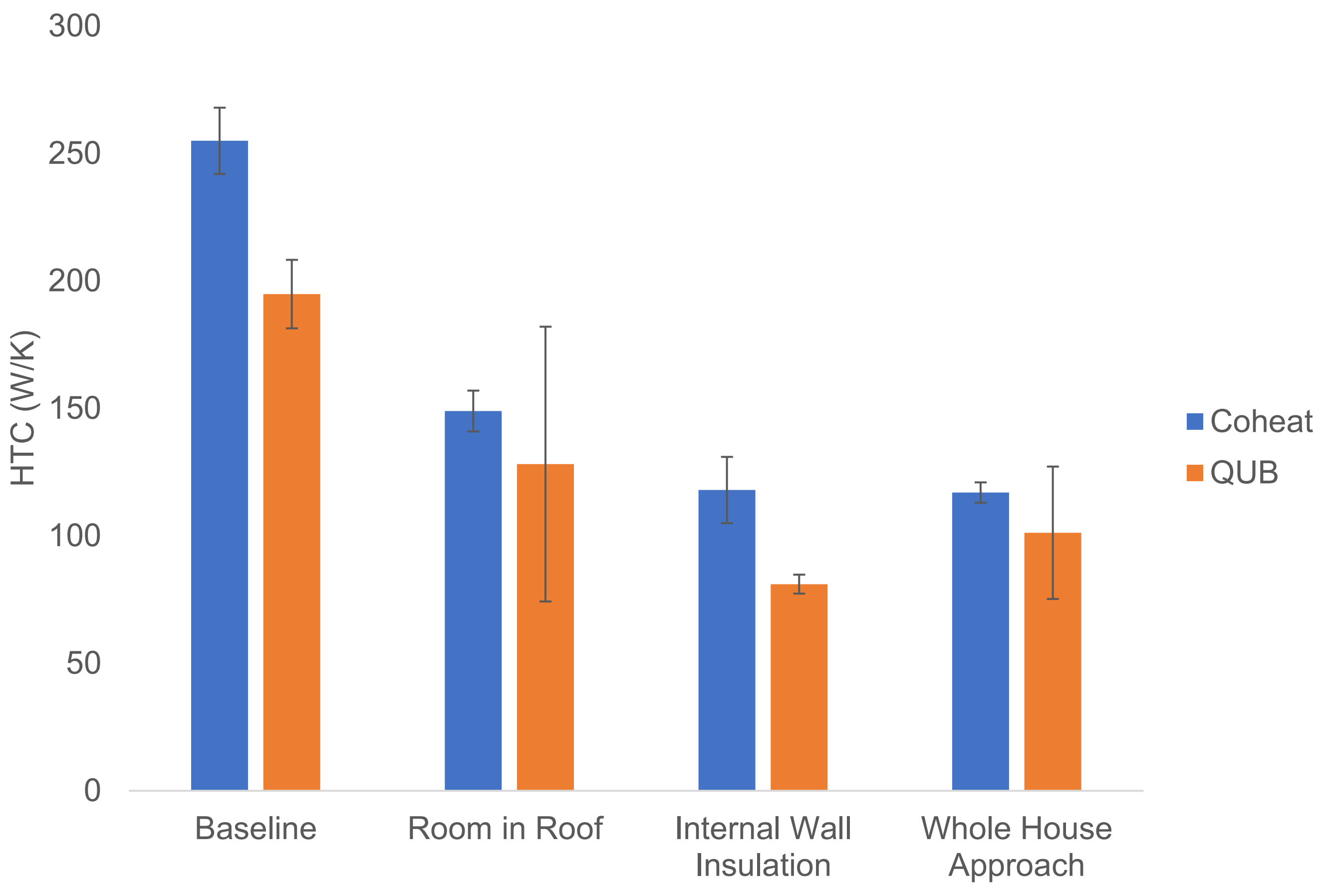

Figure 3-22 Average QUB vs coheating HTC measurements

Higher internal temperatures were observed in the coheating test compared to QUB. For the baseline tests, the coheating test used an internal setpoint of 20 °C compared to an average internal temperature of 16 °C during the QUB tests. For the three other retrofit stages under consideration in this section the coheating test used an internal setpoint of 23 °C compared to an average internal temperature of 20 °C in the QUB tests. The higher internal temperature in the coheating test could be resulting in larger infiltration losses and causing the higher HTC measurements. The dispersion of individual measurements could be attributed to varying boundary conditions and environmental conditions such as wind speed, internal/external temperature difference, and solar radiation incident on the property during the day prior to the QUB test. These variables can impact heat transfer in the property through varying infiltration rates and solar contributions stored within the fabric.

Further investigation is required to determine the cause of the difference between the HTC measurements, variation in individual measurements, and the suitability of QUB for properties of this type.

Whole house heat loss improvement summary

This section shows that the HTC of the building has been reduced substantially by the retrofits, by around (46 ± 4) %.

The airtightness and IWI retrofits were particularly successful, reducing HTC by (27 ±14) %, and (19 ± 9) % respectively. However, there is some uncertainty around the impact of the airtightness improvements due to specific difficulties with the coheating test that was undertaken.

Only marginal HTC reductions were achieved when the whole house approach measures were installed, following the IWI retrofit, since most of the fabric was already insulated.

More investigations are required to explore the heat exchange mechanisms associated with the ground floor void and basement, pre- and post-retrofit. Despite large improvements in U-values, no change in HTC was measured.

The QUB method was able to approximate similar, though slightly lower HTC values as the coheating test, albeit with more uncertainty.

3.4 Thermal bridges heat losses

Thermal bridging at all 32 junctions in 17BG, identified in Figure 3-23, 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. Default material properties were sourced from BS EN ISO 10456-2007 and BR 443.

Additionally, a brick sample was taken for analysis at 17BG so that the default λ-value for conductivity of a solid wall in could be compared to the actual conductivity found on site and the implications of any disparity considered.

There are no standard Ψ-values for existing buildings against which these calculated values could be directly compared. However, SAP 2012 Appendix K publishes these for new build constructions and a comparison with these is presented here to provide a regulatory context. 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-values calculated for 17BG.

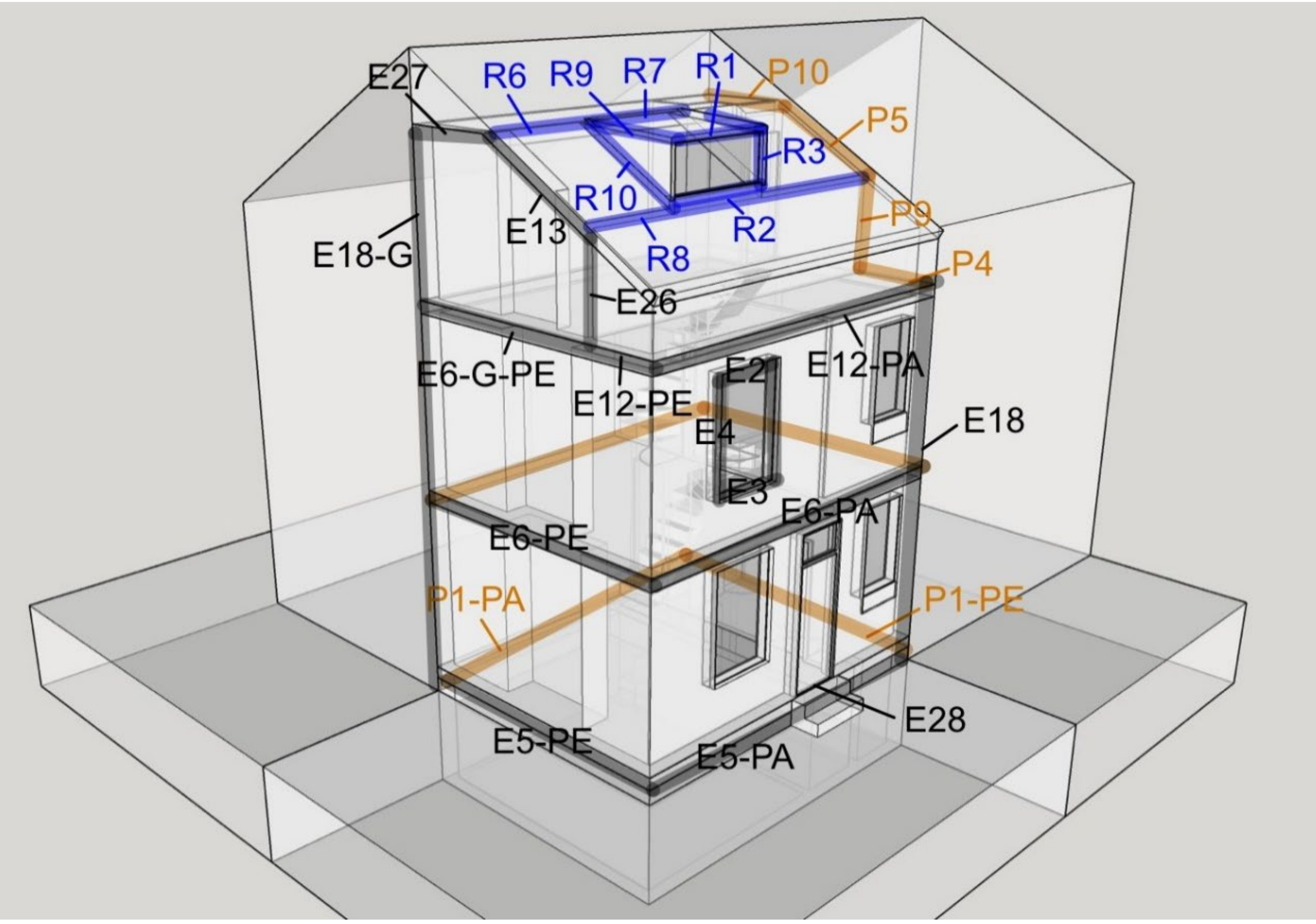

Figure 3-23 Thermal bridges (black) in 17BG including party wall (brown) and room-in-roof (blue) junctions

Each specific junction is described in Table 3-4, and the impact of each retrofit on each junction in terms of heat loss and surface condensation risk are investigated in the following section.

Table 3-4 Thermal bridging junction codes

Code	Description
E2	External wall - lintels
E3	External wall - sill
E4	External wall - jamb
E5-PE	Ground floor/external wall, joists perpendicular
E5-PA	Ground floor/external wall, joists parallel
E6-PE	External wall - intermediate floor, joists perpendicular
E6-G-PE	Gable wall - intermediate floor, joists perpendicular
E6-PA	External wall - intermediate floor, joist parallel
E12-PE	External wall - eaves, joists perpendicular
E12-PA	External wall - eaves, joists parallel
E13	Gable wall - sloped ceiling
E16	Front wall/gable wall
E18	External wall (front) / party wall
E18-G	External wall (gable) / party wall
E26	Knee wall - external wall
E27	RiR ceiling - external wall
E28	Door threshold - ground floor
P1-PE	Ground floor - party wall, joists perpendicular
P1-PA	Ground floor - party wall, joists parallel
P4	Party wall - 1st floor ceiling
P5	Party wall - sloped ceiling
P9	Knee wall - party wall
P10	RiR ceiling - party wall
R1	Dormer ceiling - dormer window opening
R2	Knee wall - dormer window opening
R3	Dormer cheek - dormer window opening
R6	Sloped ceiling - RiR flat ceiling
R7	Dormer ceiling - RiR flat ceiling
R8	Sloped ceiling - knee wall
R9	Dormer cheek - dormer ceiling
R10	Sloped ceiling - dormer cheek

3.4.1 Ψ-values; SAP 2012 Appendix K vs simulation

Figure 3-24 compares Ψ-values between Appendix K of SAP and those calculated for 17BG at each stage. As expected, there is no correlation between the calculated values for 17BG 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. This assessment suggests that Appendix K may not be suitable for existing buildings and an alternative Appendix specific to existing solid walled buildings would be needed to assess thermal bridging heal loss adequately.

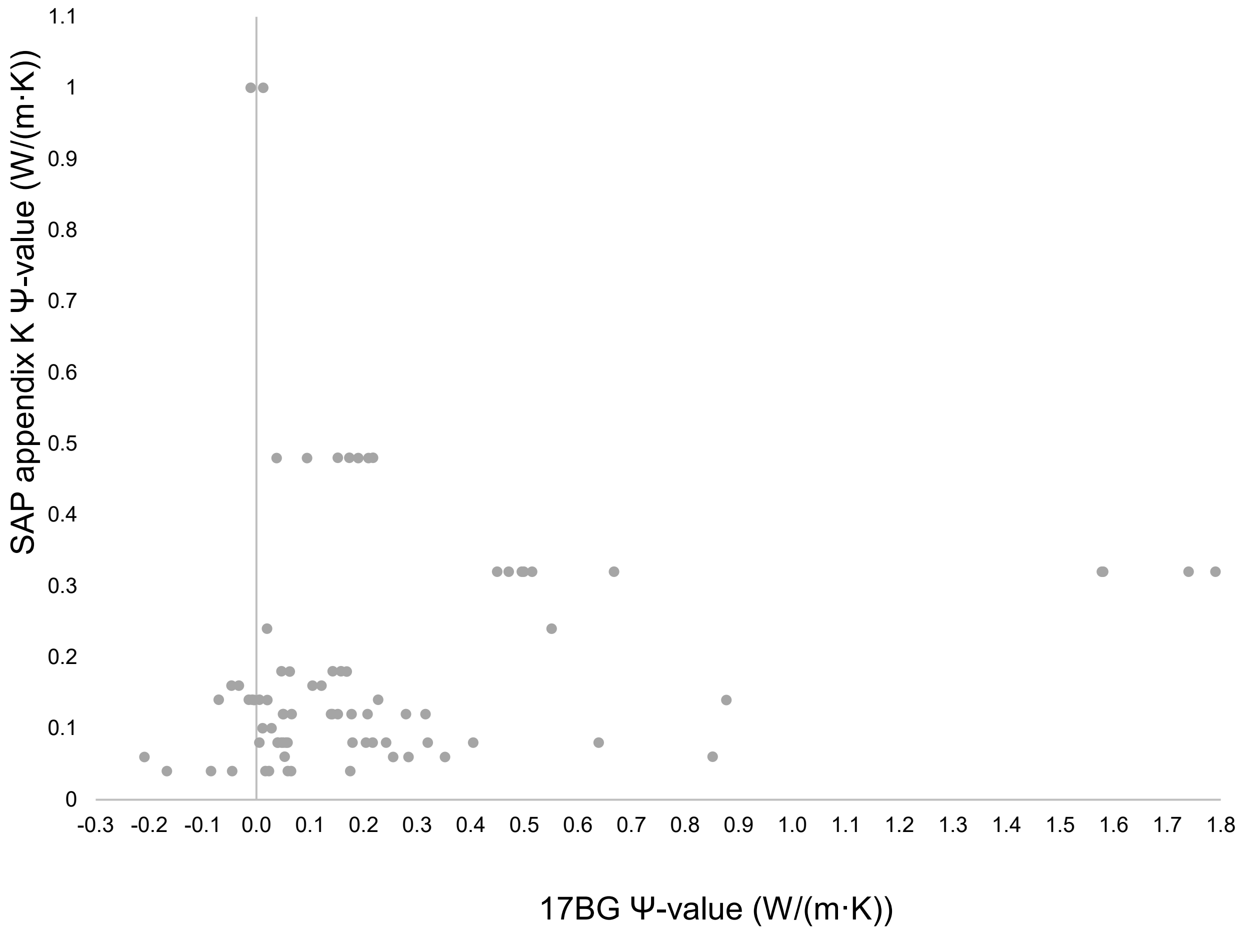

Figure 3-24: Comparison of RdSAP and 17BG Ψ-value

Junctions featuring calculated Ψ-values that are significantly different to the defaults include:

- RIR ceiling: there are no values specified in Appendix K defaults for RIR ceiling, thus, the most similar junction, E12 (gable, insulation at ceiling level) is used here for comparison.
- Window lintel: a lower Ψ-value was calculated compared with the defaults; Appendix K assumes a metal lintel is common for new-built dwellings while 17BG has stone lintels.
- Suspended timber floor junction with joist perpendicular/parallel: a significantly higher Ψ-value was predicted. The deviation may be because 17BG had an uninsulated suspended timber floor.

The details of junctions are presented in Table 3-5, which also shows the impact that retrofitting at the junctions can have - often reducing, though in some instances increasing, Ψ-values.

Table 3-5 Summary of Ψ-values for 17BG

Junction	Ψ-value					
	Appendix K	17BG.B	17BG.R	17BG.F	17BG.W	17BG.WH
External wall – lintels	1.00	0.013			-0.010	
External wall - sill	0.08	0.405			0.179	
External wall - jamb	0.10	0.029			0.012	
Door threshold - ground floor	0.32	0.515		0.668		
External wall - intermediate floor, joists perpendicular	0.14	-0.070			-0.004	
Gable wall - intermediate floor, joists perpendicular	0.14	-0.070	0.877		-0.014	
External wall - intermediate floor, joist parallel	0.14	0.006			-0.007	
External wall - eaves, joists perpendicular	0.48	0.119			0.049	
External wall - eaves, joists parallel	0.48	0.149			0.059	
Gable wall- Sloped ceiling -base case	0.08	0.205	0.058			0.040
Front wall /gable wall	0.18	0.143			0.047	
External wall (front) / party wall	0.12	0.178				0.152
External wall (gable) / party wall	0.12	0.208			0.142	
External wall (gable RiR) / Party wall	0.12	0.140	0.050			
Ground floor /external wall, joists perpendicular	0.32	1.579		0.450	0.499	
Ground floor / external wall, joists parallel	0.32	1.581		0.471	0.496	
Knee wall - external wall	0.18	0.158	0.063			
RiR flat ceiling - external wall	0.48	0.162	0.060			0.038
Ground floor - party wall, joists perpendicular	0.16	0.122		-0.046		
Ground floor - party wall, joists parallel	0.16	0.106		-0.033		
Party wall - 1st floor ceiling	0.24	0.552	0.020			
Party wall - sloped ceiling	0.08	0.320				0.217
Knee wall - party wall	0.12	0.316	0.280			
RiR flat ceiling - party wall	0.08	0.640				0.242
Dormer ceiling - dormer window opening	0.08	0.08	0.056			0.051
Knee wall - dormer window opening	0.06	-0.981	0.353			
Dormer cheek - dormer window opening	0.08	0.040	0.047			0.006
Sloped ceiling - RiR flat ceiling	0.06	0.852				-0.209
Dormer ceiling - RiR flat ceiling	0.04	-0.045				0.175
Sloped ceiling - knee wall	0.06	0.053	0.255			0.284
Dormer Cheek - dormer ceiling	0.04	0.065	0.059			0.024
Sloped ceiling - dormer cheek	0.04	-0.166	0.017			-0.084

3.4.2 Thermal bridging heat loss: HTC_b pre- vs post-retrofit

Absolute heat loss from a thermal bridge (HTC_b) is calculated by multiplying the Ψ-value by the length of a junction. Figure 3-25 shows the change in HTC_b for individual junctions, comparing post-retrofit values with the pre-retrofit baseline case. In most instances, the insulation reduces heat loss, though there are notable exceptions where there were discontinuities in the insulation layers around the dormer and knee walls, intermediate floors, and door threshold.

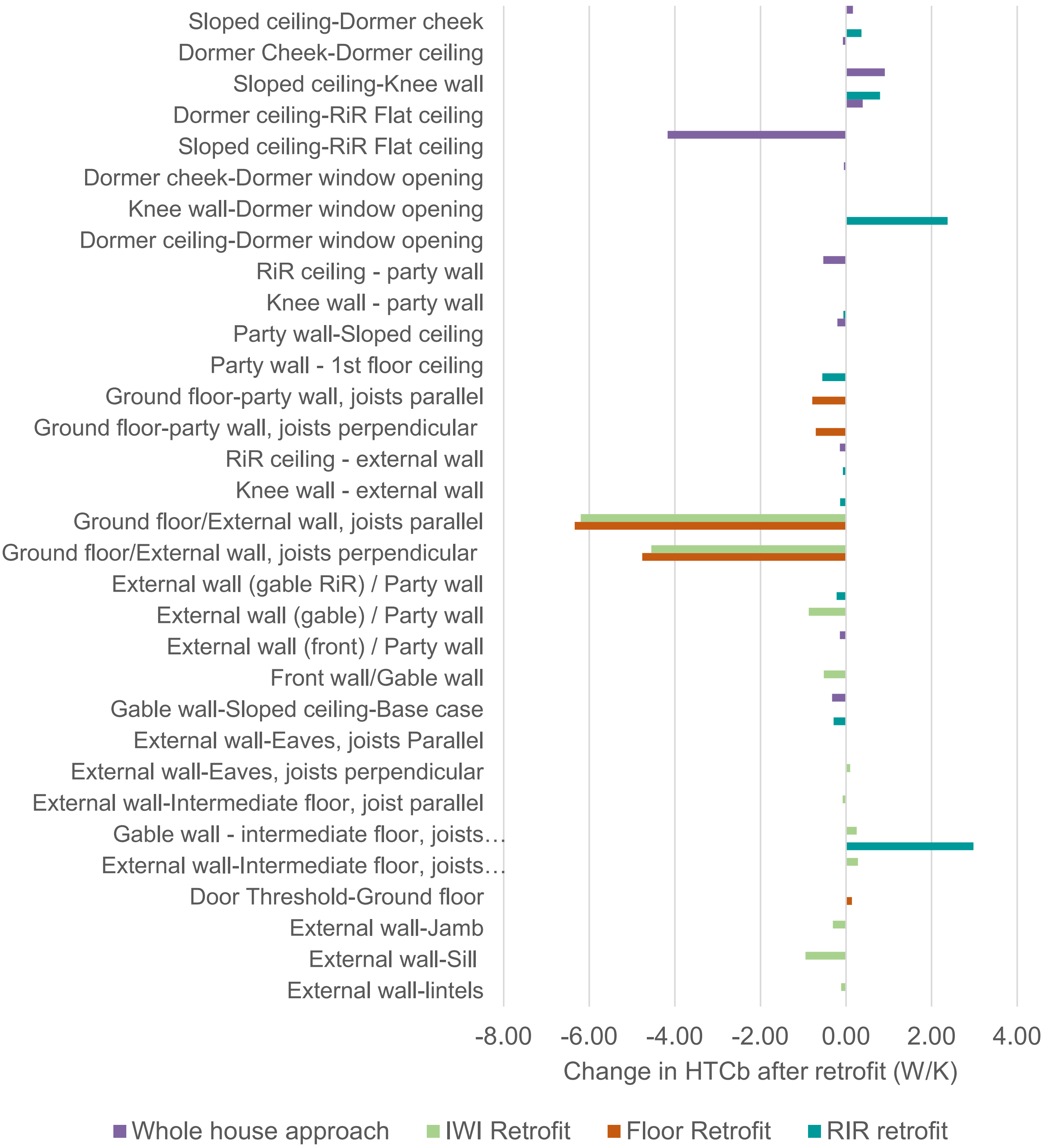

Figure 3-25: Change in thermal bridging after retrofit in 17BG

3.4.3 Thermal bridging heat loss: y-values

RdSAP and EPCs do not use HTC_b to attribute heat loss for thermal bridges, 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 W/(m·K). 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 17BG and compare these with the 0.15 default.

HTC_b and y-values for 17BG are shown in Table 3-6. The default value of 0.15 underestimates heat loss in the uninsulated state, but overestimates heat loss when the house is fully insulated. 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.

When a whole house approach was undertaken, heat loss from bridges was reduced by over 50 %. Indeed, all the retrofit stages reduced thermal bridging heat losses from the house, except the RIR stage. A relatively small number of specific junctions, where a continuous insulation layer was not maintained after retrofit, were responsible for this increase. More research may be needed to identify all such problem junctions, and common solutions to avoid increased bridging at these areas could be developed.

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 3-6 Calculated HTC_b and y-value after each retrofit stage

Retrofit stage	HTC_b (W/K) default properties	HTC_b (W/K) measured properties	y-value default material properties	y-value measured material properties
17BG.B (Base case)	25.6	25.7	0.20	0.20
17BG.A.R (Room-in-roof insulation)	31.0	31.7	0.24	0.24
17BG.A.R.F (Suspended timber ground floor insulation)	20.1	19.8	0.16	0.15
17BG.A.R.F.W (Internal wall insulation)	14.7	15.1	0.11	0.12
17BG.A.R.F.W.WH (Whole house approach measures)	10.7	11.4	0.08	0.09

EPCs do not consider there to be any change in thermal bridging heat loss due to retrofits. However, the calculated change in HTC_b from uninsulated to whole house approach retrofit was around 15 W/K, the same order of magnitude as the room-in-roof retrofit.

To generate Ψ-values for a single home is burdensome, and while EPCs could be more accurate to calculate a bespoke y-value for a home, it would not be practical or cost effective. Thermal bridging, therefore, may remain an area of inaccuracy for EPCs.

More research is needed to understand if the trends in y-values observed here are found in other home construction types. If this was commonly observed, it may be appropriate to develop a wider range of default y-values for different house types and retrofit statuses, for use in EPCs, to improve their accuracy without requiring costly and time-consuming modelling.

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 at risk. The temperature factor (f_{Rsi}) is calculated using Equation 2:

Equation 2 Temperature factor 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).

Table 3-7 shows the temperature factor (f_{Rsi}) of the 32 thermal bridges modelled for each retrofit stage. The junctions with f_{Rsi} below 0.75 are highlighted red, indicating they may have the risk of surface condensation.

In the uninsulated home, 71 % of junctions had f_{Rsi} lower than 0.75 with the roof junctions performing the worst, with 86 % of the roof junctions at risk of condensation (f_{Rsi}<0.75). This confirms previous work that identifies that condensation risk may already exist in uninsulated solid wall homes.

After the whole house approach retrofit, the majority of junctions had a f_{Rsi} above or approaching 0.75, except door threshold-ground floor junction. This shows the potential success of adopting whole house approach retrofits to remove condensation risks in solid wall homes, though more research is needed to investigate if this is the case in other building types.

It is interesting to note that condensation risks were removed, even when relatively small levels of insulation are used. For example, pre-existing thin IWI in 17BG was installed on the front wall (parallel joists) and no risk was found at the wall floor junction here, yet it was not installed on the gable wall (perpendicular joists), but this was at risk of condensation.

The most at-risk junction was the door threshold, and this worsened after the retrofits were completed, since the threshold was not insulated. Swapping existing stone thresholds for insulated thresholds or insulating existing thresholds is not a common retrofit measure, though this research suggests it could be a beneficial area for future innovation.

Table 3-7 Temperature factor (f_{Rsi}) after each retrofit stage (red = potential risk)

Element	Junction	17BG.B	17BG.R	17BG.R.F	17.BG.R.F.W	17.BG.R.F.W.WH
Windows and Doors	External wall - lintels	0.850			0.919	
	External wall - sill	0.823			0.912	
	External wall - jamb	0.698			0.877	
	Door threshold - ground floor	0.356			0.284	
Floors	External wall - intermediate floor, joist perpendicular	0.724	0.634		0.904	
	External wall - intermediate floor, joist parallel	0.772			0.869	
	Ground floor -external wall, joist perpendicular	0.709		0.697	0.833	
	Ground floor - external wall, joist parallel	0.818		0.796	0.854	
	Ground floor - party wall, joist perpendicular	0.936		0.939		
	Ground floor - party wall, joist parallel	0.947		0.938		
Walls	External wall - eaves, joist perpendicular	0.638			0.785	
	External wall - eaves, joist parallel	0.750			0.807	
	Gable wall - sloped ceiling	0.619	0.800			0.852
	Corner (normal)	0.606			0.836	
	External wall (front) - party wall	0.784			0.826	
	External wall (gable) - party wall	0.738			0.824	
Room-in-roof	Knee wall - external wall	0.479	0.630		0.851	

Element	Junction	17BG.B	17BG.R	17BG.R.F	17.BG.R.F.W	17.BG.R.F.W.WH
	RIR ceiling external wall	0.643			0.854	0.906
	Party wall - FF ceiling	0.788	0.860			
	Party wall - sloped ceiling	0.742				0.800
	Knee wall - party wall	0.561	0.763[8]			
	RIR ceiling - party wall	0.578				0.798
	Dormer ceiling - dormer window opening	0.702	0.735			
	Knee wall - dormer window opening	0.591			0.779	
	Dormer cheek - dormer window opening	0.643	0.700			0.907
	Sloped ceiling - RIR flat ceiling	0.446				0.871
	Dormer ceiling - RIR flat ceiling	0.600				0.875
	Sloped ceiling - knee wall	0.508			0.821	0.797
	Dormer cheeks - dormer ceiling	0.704			0.763	0.852
	Sloped ceiling - dormer cheek	0.793			0.851	0.919

[8] When measured material properties are used in place of the TRISCO defaults this value drops to 0.744, which may indicate a condensation risk

3.4.5 Thermal bridging alternative scenarios

Alternative retrofit scenarios were investigated, in addition to those undertaken at 17BG, to explore the potential heat loss and condensation risks that might occur under different retrofit approaches. Table 3-8 shows that floor to solid wall junctions have higher heat losses when floors and walls are uninsulated, and that this increases marginally when IWI is installed without insulating floors at the same time.

Table 3-8 Influence of different IWI retrofit approaches

Element	Junction	Ψ-value (W/(m·K))	HTC_b (W/K)	f_{Rsi}
Suspended timber floor (joist perpendicular)	Uninsulated wall, uninsulated floor	1.58	6.66	0.71
	Uninsulated wall, insulated floor	0.45	1.90	0.70
	IWI, insulated floor	0.50	2.10	0.83
	IWI, uninsulated floor	1.79	7.55	0.85
Party wall between dwellings (gable wall)	uninsulated wall	1.64	0.21	0.74
	IWI	0.77	0.14	0.82
	IWI plus return	0.277	0.05	0.90

Condensation risk is also present at this junction when floors and walls are uninsulated. However, the risk is removed when walls are insulated, even if the floor is left uninsulated. Conversely, leaving walls uninsulated and insulating floors does not remove this risk.

Table 3-8 also shows that uninsulated solid wall to party wall junctions may pose a condensation risk and are a source of thermal bridging heat loss. When undertaking IWI retrofits, returning the IWI back along the first section of party walls is commonly undertaken to reduce thermal bridges. Adding a return is an approach often taken to reduce heat loss and condensation risk, though here it is suggested that the IWI without a return was also successful in reducing condensation risk.

Thermal bridging heat loss improvement summary

The work confirmed that SAP 2012 default Ψ-values in Appendix K may not always reflect Ψ-values simulated numerical thermal simulation. This is especially the case where historic building junctions differ from more modern construction details, for example, for room-in-roof junctions and lintels, where much more heat loss was calculated than the defaults suggest. After retrofits had taken place Ψ-values were reduced, except where there was a discontinuity in the insulation layer.

The y-value of the uninsulated home was calculated to be 0.20, meaning the RdSAP default y-value of 0.15 underpredicts heat loss from thermal bridging. However, after the retrofits the calculated y-value of the house was reduced to 0.08, illustrating that there can be lower thermal bridging heat loss post retrofit.

It may be appropriate to have alternative y-value defaults to account for different homes at differing states of insulation. The development of any alternative y-value defaults is likely to require a broader range of scenarios than simply ‘insulated’ and ‘uninsulated’, to reflect the heterogeneity that can exist in the housing stock.

Uninsulated solid wall homes have condensation risks in around three quarters of junctions. These risks can be removed when a whole house approach to retrofit is undertaken. Rooms-in-roof have particularly high surface condensation risks, and some of these can persist after insulation is added. =However, the door threshold is the junction with the greatest risk of surface condensation.

IWI can increase thermal bridging heat loss at the floor junction, though it may remove condensation risk.

3.5 Measured vs. 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 HTC_f 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 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 HTC_f 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 HTC_b.
- Systematic uncertainty in the coheating test cannot be perfectly accounted for, e.g., party wall heat exchange, solar gains; plus 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, in order 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, HTC_f and HTC_b are presented in Figure 3-26.

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 U-value (W/(m²·K)), the HTC_v is previously described in Equation 1, and calculating the HTC_b using the thermal software is described in the previous chapter.

As can be seen, fabric heat loss is generally responsible for over two thirds of whole house heat loss in this house; how much of the remaining heat loss is due to infiltration and bridging depends on the retrofit stage.

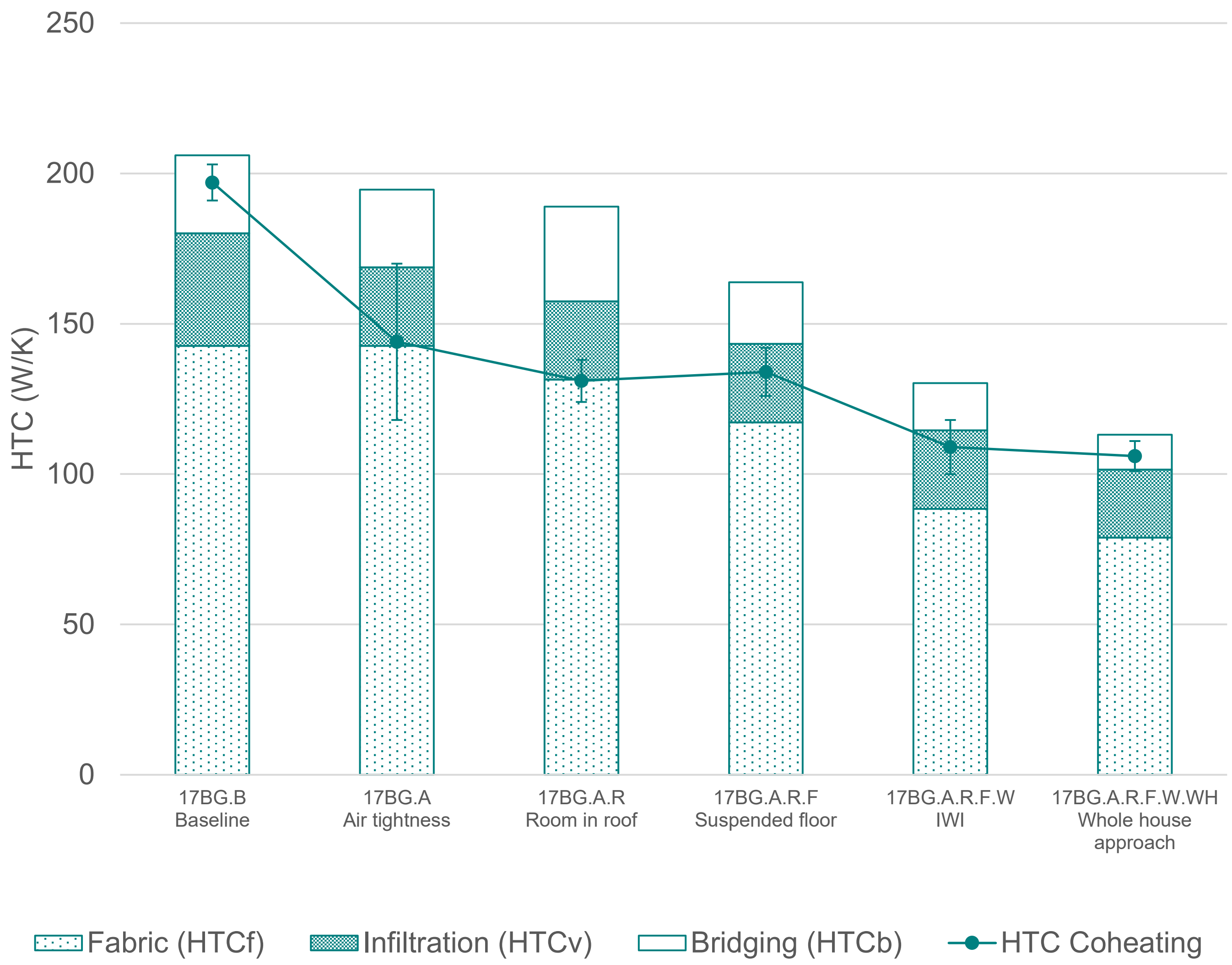

Figure 3-26 Aggregated vs. disaggregated measured HTC

The HTC measured by the coheating test was shown to be somewhat different to 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 was greater than the coheating HTC in all retrofit stages, indicating uncertainties in the closing-the-loop method.
- The benefit of the airtightness retrofit was substantially lower using the n/20 rule of thumb to calculate HTC_v than the coheating HTC reported.
- Uncertainty in the blower door test and air exchanges with neighbours may have overestimated HTC_v.
- Heat flux density plates are not able to capture heterogeneity in heat loss from fabric elements (repeated, or local bridges, local bypasses, or varying insulation thickness), meaning U-values and HTC_f may have been overestimated in this house.
- Heat flux density measurements to unheated spaces such as basements, the knee wall, and loft space may result in U-values that are not representative of the heat loss to the outside and so overestimate HTC_f.
- The floor retrofit substantially reduced HTC_f, though did not register a change in the coheating test HTC. More work into suspended timber floor heat losses is needed.

The proportion of heat lost via fabric, infiltration and bridging varies according to the retrofit stage as shown in Table 3-9. The RIR retrofit was the only retrofit to cause additional bridging heat loss since it has many junctions, complex geometry and discontinuities in the insulation layer. All other retrofits reduced the amount of bridging heat loss, although if a whole house approach is not adopted, retrofits may increase the relative importance of HTC_b to whole house heat loss.

Table 3-9 Whole house heat loss via disaggregated methods

Retrofit stage	HTC_f W/K	HTC_v W/K	HTC_b W/K
17BG.B Base case	143 (69 %)	37 (18 %)	26 (13 %)
17BG.A Airtightness improvement	143 (73 %)	26 (13 %)	26 (13 %)
17BG.A.R Room-in-roof insulation	131 (70 %)	26 (14 %)	31 (17 %)
17BG.A.R.F Suspended timber ground floor insulation	117 (72 %)	25 (16 %)	21 (13 %)
17BG.A.R.F.W Internal wall insulation	88 (68 %)	26 (20 %)	16 (12 %)
17BG.A.R.F.W.WH Whole house approach measures	79 (70 %)	23 (20 %)	12 (10 %)

The next section discusses how the different pieces of 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: RdSAP defaults

In this step the default input values for airtightness and U-values are used. In Figure 3-27 the measured HTC values for each retrofit stage are plotted against the HTC values predicted by the uncalibrated models using default RdSAP input data. It indicates that:

- HTC is substantially overestimated when using defaults in all models, in part because thin amounts of insulation are not captured.
- Using default room-in-room geometry supported in RdSAP, rather than inputting detailed measurements, causes the substantial overestimate of heat loss. This is shown as the difference between RdSAP and BREDEM in the pre-room-in-roof retrofit stages.
- RdSAP and BREDEM show slight variations in other stages due to inbuilt geometry assumptions, i.e., excluding chimneys and impacting how floor U-values are calculated.
- RdSAP and BREDEM overestimate HTC by more than DSM.
- The difference between steady-state and dynamic HTC predictions, and between modelled and measured HTC, reduces as the home is retrofitted.
- Models predict a reduction in HTC from floor retrofits, but this was not measured in-situ.
- Airtightness improvements have no impact on HTC if default inputs are used, as infiltration is fixed in RdSAP.

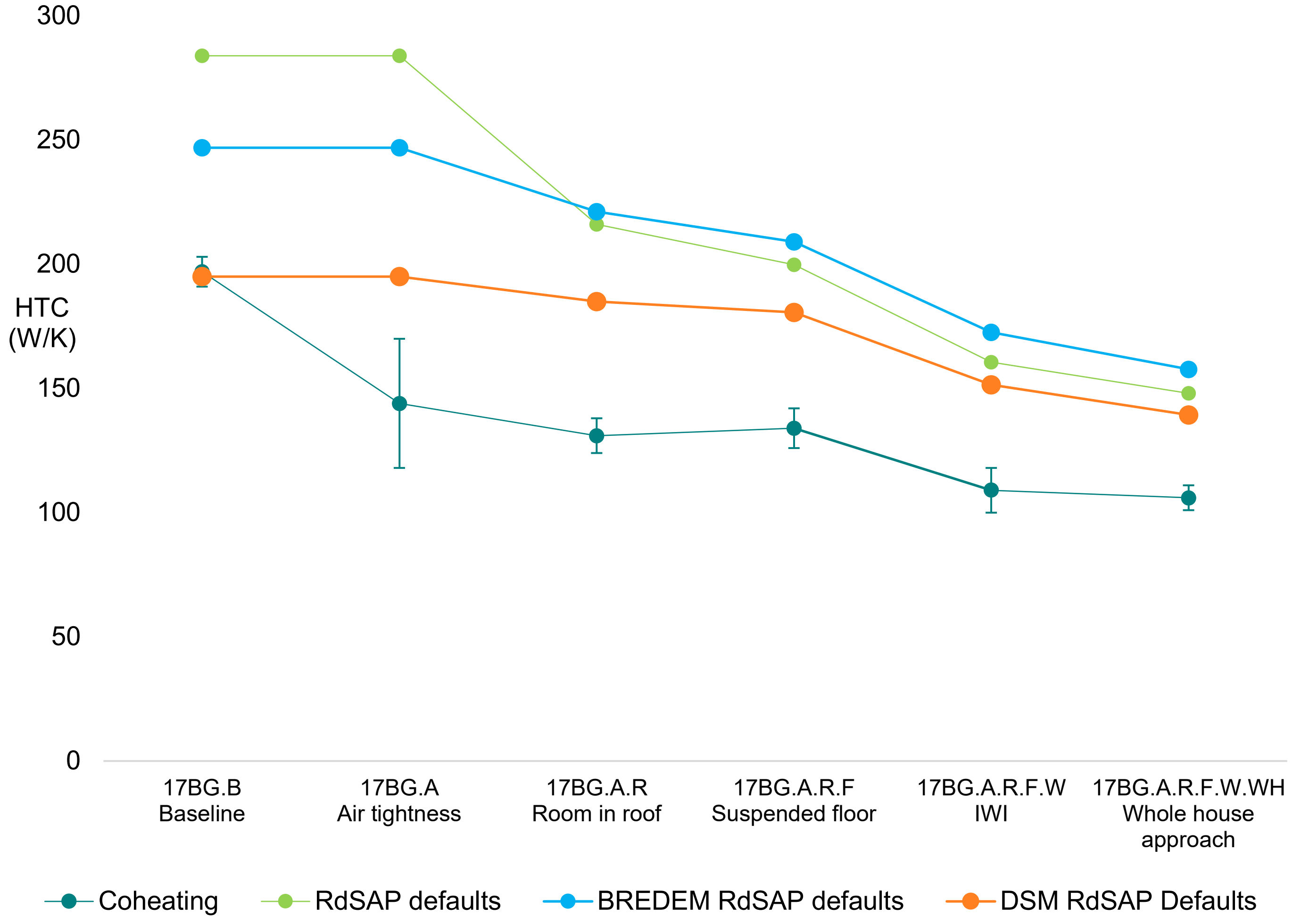

Figure 3-27 Measured vs modelled HTC calibration step 1: default data

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 these data are the most likely to be acquired in practice. The impact of this compared to the previous calibration stage can be seen in Figure 3-28:

- RdSAP is not included in this calibration step as infiltration cannot be altered in software.
- HTC predictions get closer to measured values when measured infiltration is included.
- Including infiltration still results in overpredictions in HTC values for this case study home when default RdSAP fabric values are retained.
- Predicted reductions in HTC achieved by the airtightness retrofit are smaller than were measured by the coheating test, even when measured infiltration rates are used in models, perhaps reflecting the uncertainty in this coheating test.

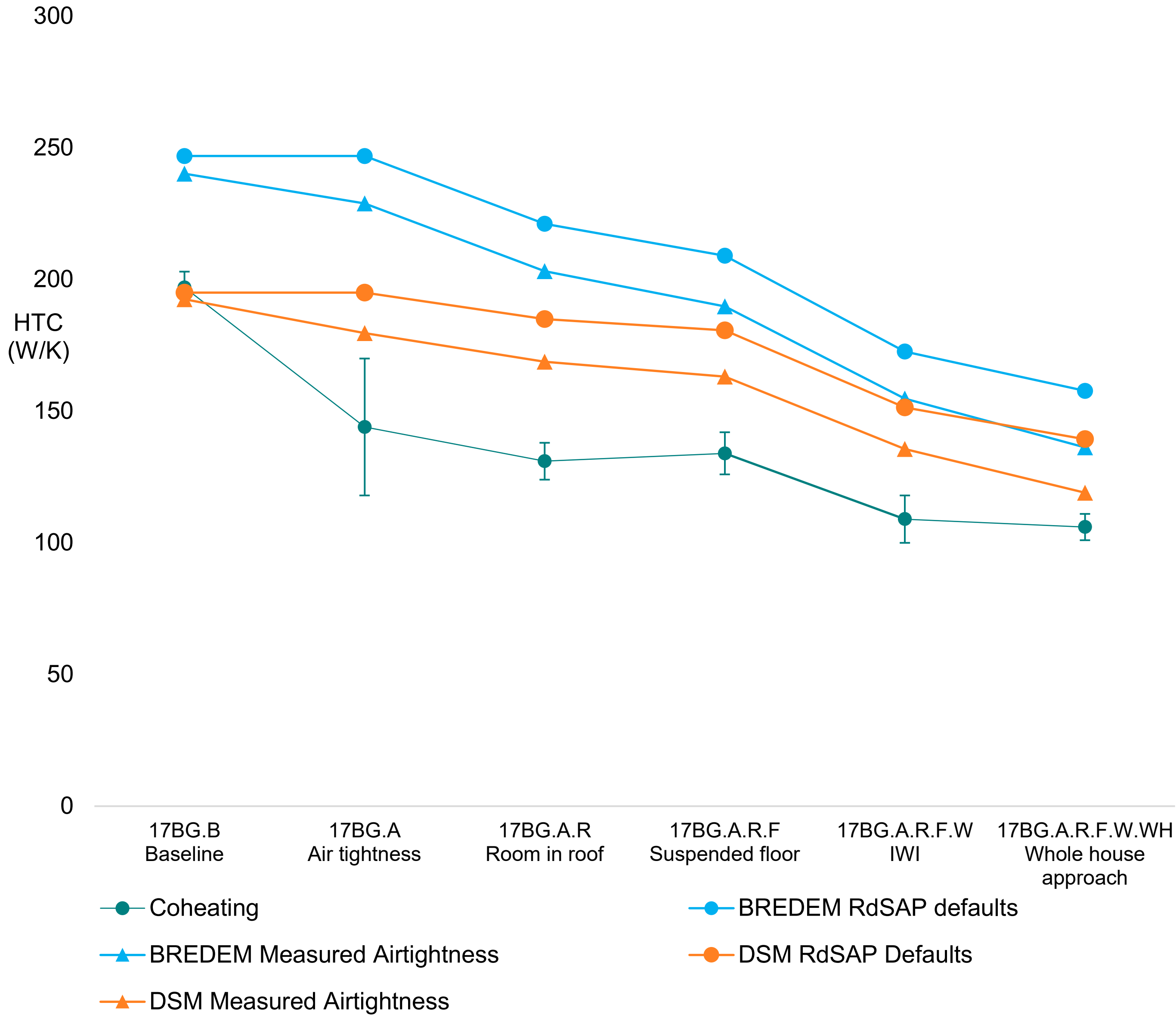

Figure 3-28 Measured vs modelled HTC calibration step 2: measured infiltration

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 needs more detailed surveys. It often requires 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 3-29:

- Using calculated U-values further reduces the gap between modelled and measured HTC.
- The improvement in prediction is most impactful for uninsulated elements.
- Predictions using calculated U-values are much more meaningful in estimating HTC and predicting retrofit savings.
- RdSAP is again not included in this calibration step, as only measured U-values can be used under the conventions.

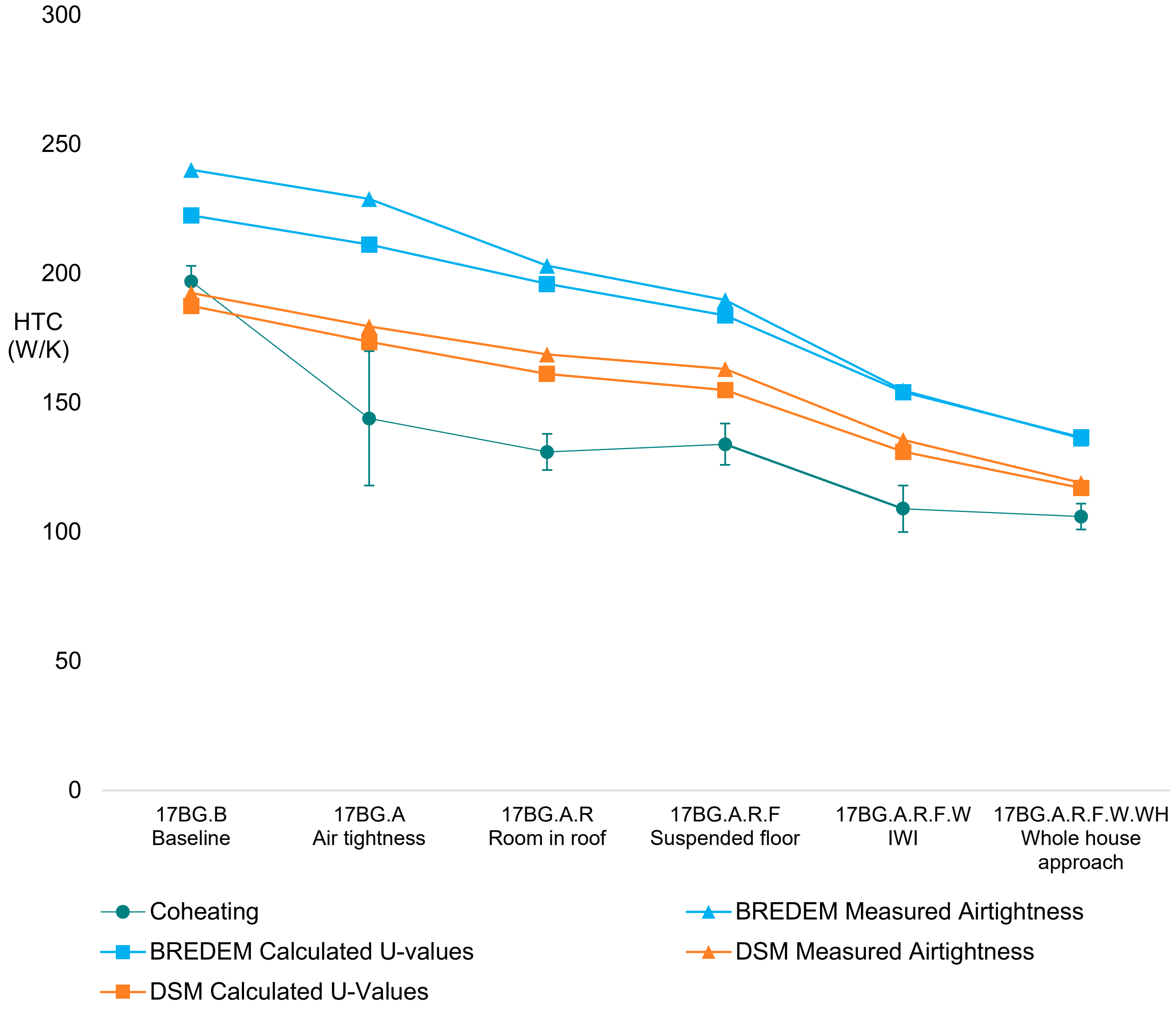

Figure 3-29 Measured vs modelled HTC calibration step 3: calculated U-values

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

In this step, the models used measured U-values which required resource intensive in-situ testing. The impact of this compared to the previous calibration stage is shown in Figure 3-30:

- Using measured U-values in RdSAP and BREDEM substantially improves HTC predictions.
- The baseline model predictions are almost within the uncertainty of the coheating test.
- Only a slight change in HTC was predicted by DSM when using measured U-values rather than calculated U-values.
- Even with measured U-value and airtightness values, the models still over predict the HTC compared to the coheating test.

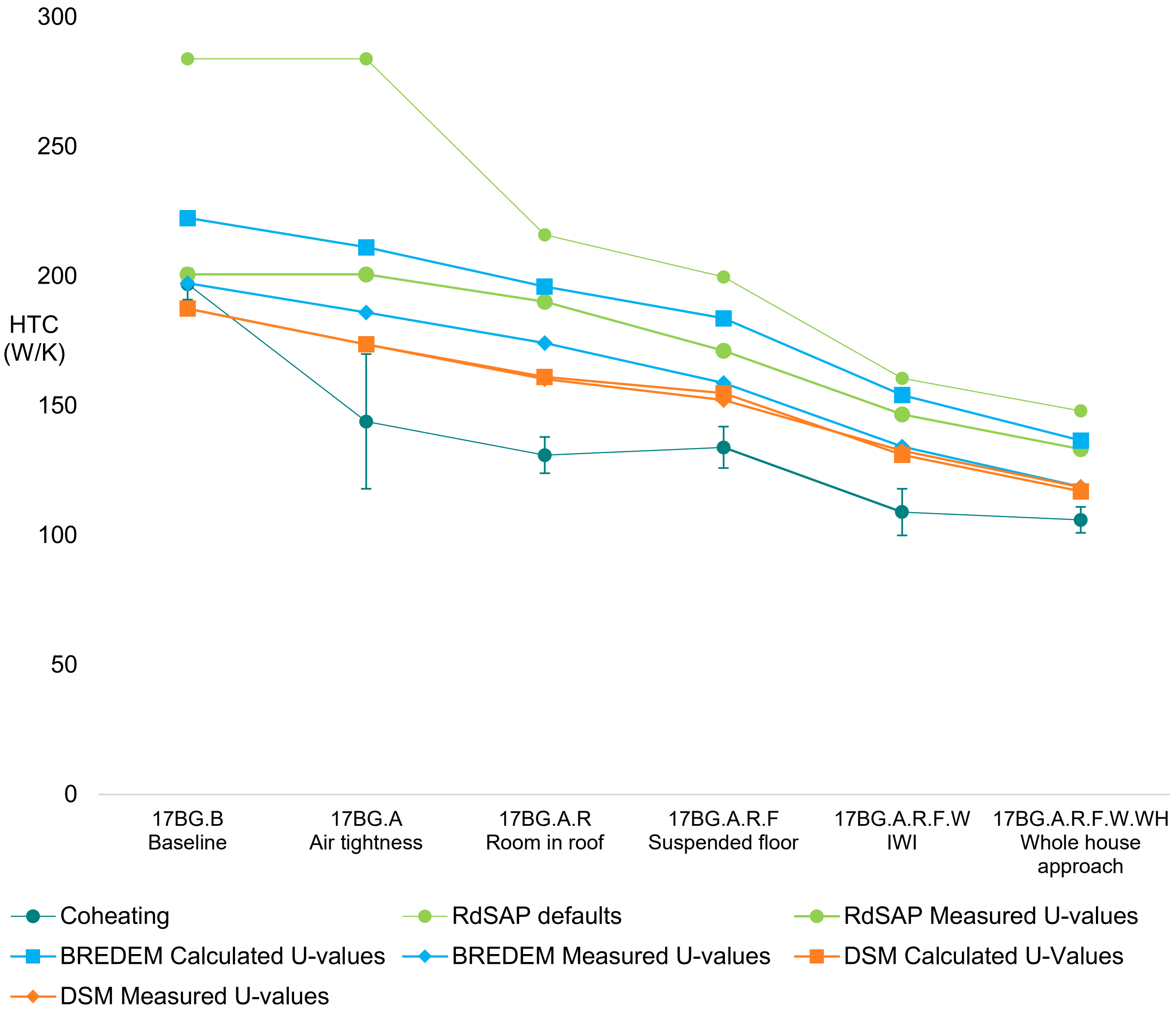

Figure 3-30 Measured vs modelled HTC calibration step 4: measured U-values

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 3-31:

- Retrofits may increase or reduce HTC_b depending on how many discontinuities in the insulation there are, e.g., RIR retrofits increased HTC_b.
- Using the calculated HTC_b in some instances brings modelled values closer to the measured HTC, though sometimes not.
- y-values used in BREDEM appear to under predict thermal bridging heat loss in uninsulated homes and over predict heat loss in insulated homes.
- Default thermal bridging in DSM tends to over predict HTC_b, regardless of retrofit stage.
- RdSAP is not included in this stage as y-values are fixed and cannot be altered.

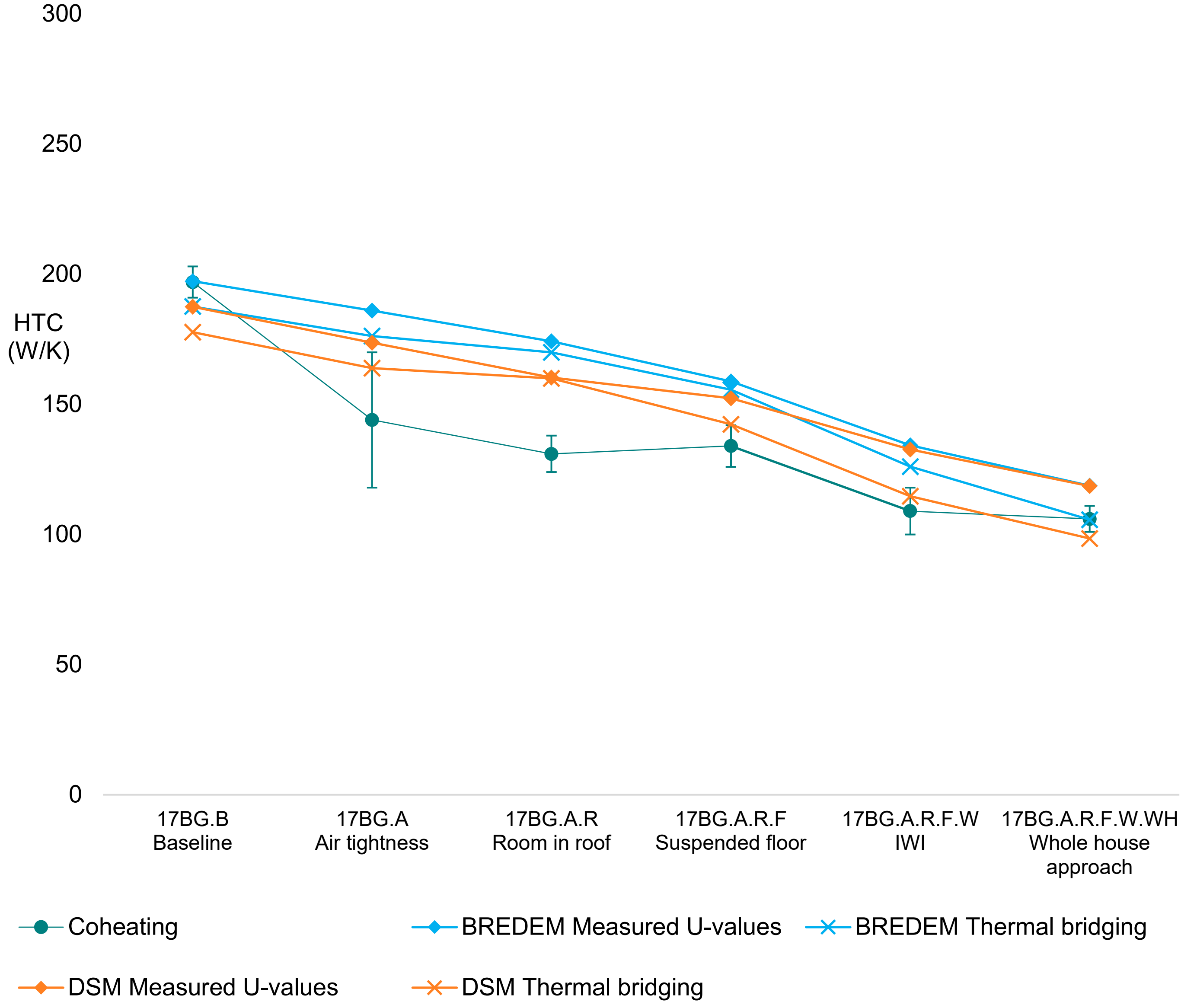

Figure 3-31 Measured vs modelled HTC calibration step 5: calculated thermal bridging

It is worth noting that the DSM models did not include the bathroom and kitchen wall insulation until the whole house (WH), since input methods in DSM limit the ability to insulate parts of elements. This may cause an overestimation of HTC in the retrofits before the whole house stage. Also, the total conditioned floor area in the DSM model was slightly smaller (by 2.6 m^2) than in steady-state models, as the chimneys were included in the model geometry as an unconditioned semi-exterior space. This will have had a minor impact on total heat demand.

Measured versus modelled HTC summary

The closing-the-loop analysis shows a discrepancy in the coheating HTC compared to the HTC derived from the blower door, U-value measurements, and thermal bridging calculations. More research is needed to understand the accuracy of disaggregated methods to calculate whole house HTC, especially the n/20 rule of thumb.

The study has confirmed that using default values can overestimate the HTC compared to using measured values, and thus results in overestimates of retrofit savings.

Replacing defaults with measured data reduces, or in some instances removes, the prediction gap and provides more accurate retrofit saving predictions.

EPC assessors are able to use inbuilt assumptions around room-in-roof dimensions, rather than inputting all the measurements for each surface. However, this was found to overestimate heat losses, and this was the biggest single cause of the prediction gap. Revising these conventions could substantially improve the accuracy of EPCs for homes with rooms-in-roof.

RdSAP ignores thin internal wall insulation so can over predict U-values. Using measured (or calculated) U-values, makes the next biggest improvement in the HTC predictions.

As elements are retrofitted fewer default values are used, which reduces the prediction gap, i.e. pre-retrofitted EPCs have bigger prediction gaps.

The models predicted similar savings to those measured for the cumulative retrofits undertaken and for the individual IWI retrofit. However, the models over predicted the benefit of the floor insulation and the whole house approach retrofits, while it underpredicted the benefit of the room-in-roof and airtightness retrofits.

The RdSAP default airtightness prediction was relatively close to the measured value for this house. However, the benefits of reducing infiltration through retrofits are ignored.

RdSAP could include measured airtightness data, in the same way as BREDEM. This would improve the accuracy of EPCs and allow the benefits of airtightness improvements to be predicted.

All models over predicted HTC compared to the coheating test. For this house, however, DSM has a smaller prediction gap than BREDEM and RdSAP.

Although the HTC values from the calibrated BREDEM and DSM models had low prediction gaps, there is still some discrepancy.

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 those defined in the RdSAP conventions, which are described in the DEEP Methods 2.01 Report. This is to provide a useful comparison between the modelling approaches, based upon changes to fabric inputs only. However, as shown in Figure 3-32, despite having matching assumptions for gains and occupancy, the resulting space heating demand from the RdSAP, BREDEM and DSM models differ 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 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 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; since RdSAP age band default data underestimates baseline EPC scores and thus overestimates retrofit savings.

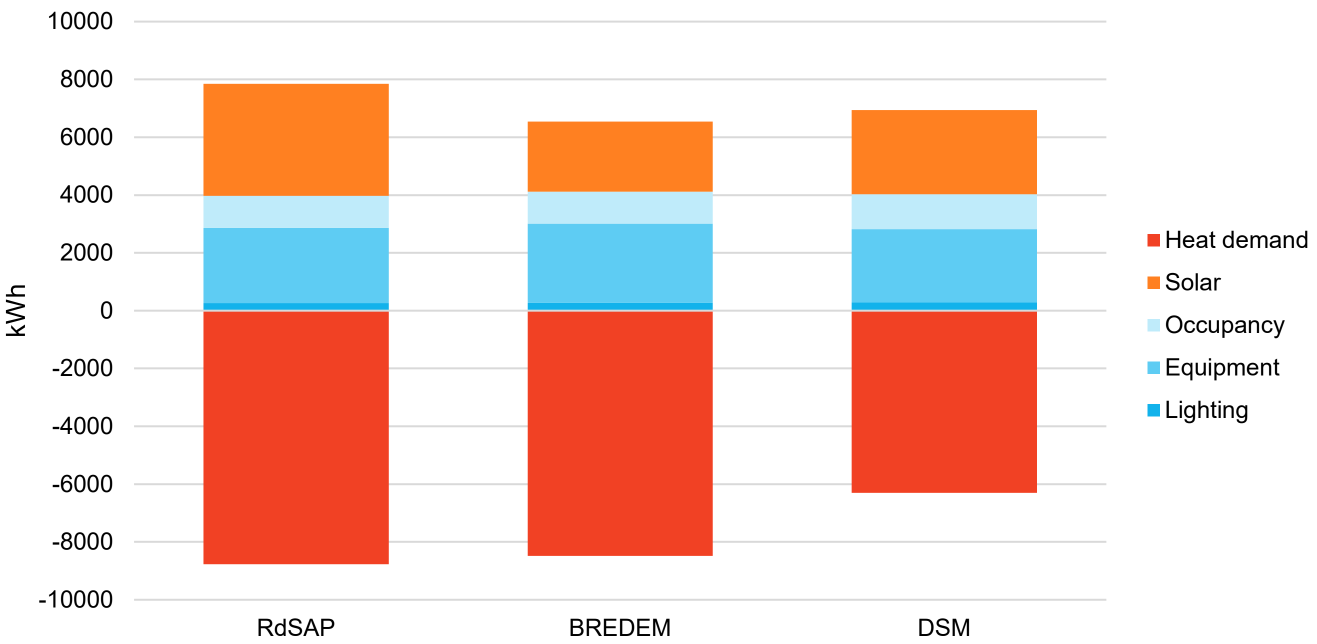

Figure 3-32 Annual heat gains and space heating demand in baseline RdSAP, BREDEM and DSM models

3.6.1 Impact of retrofits on EPC bands

Several policy mechanisms set EPC targets, and the Government has an ambition that all homes (where practically possible) will achieve an EPC band C by 2035 [13]. The impact of the retrofits on EPC in this case study, as predicted by each model at each calibration stage, is shown in Figure 3-33 and the salient points are described below:

- Steady-state models predict lower EPC bands than DSM.
- The pre-existing thin IWI achieves an EPC D when considered in all models.
- The IWI achieves an EPC band C in DSM and RdSAP even when defaults are used.
- The whole house retrofit achieves an EPC band C in all models except when default U-values are used in BREDEM.
- No retrofits in any models, using any data, achieve an EPC B rating.
- The EPC is most improved by the IWI since this house had an uninsulated gable wall.

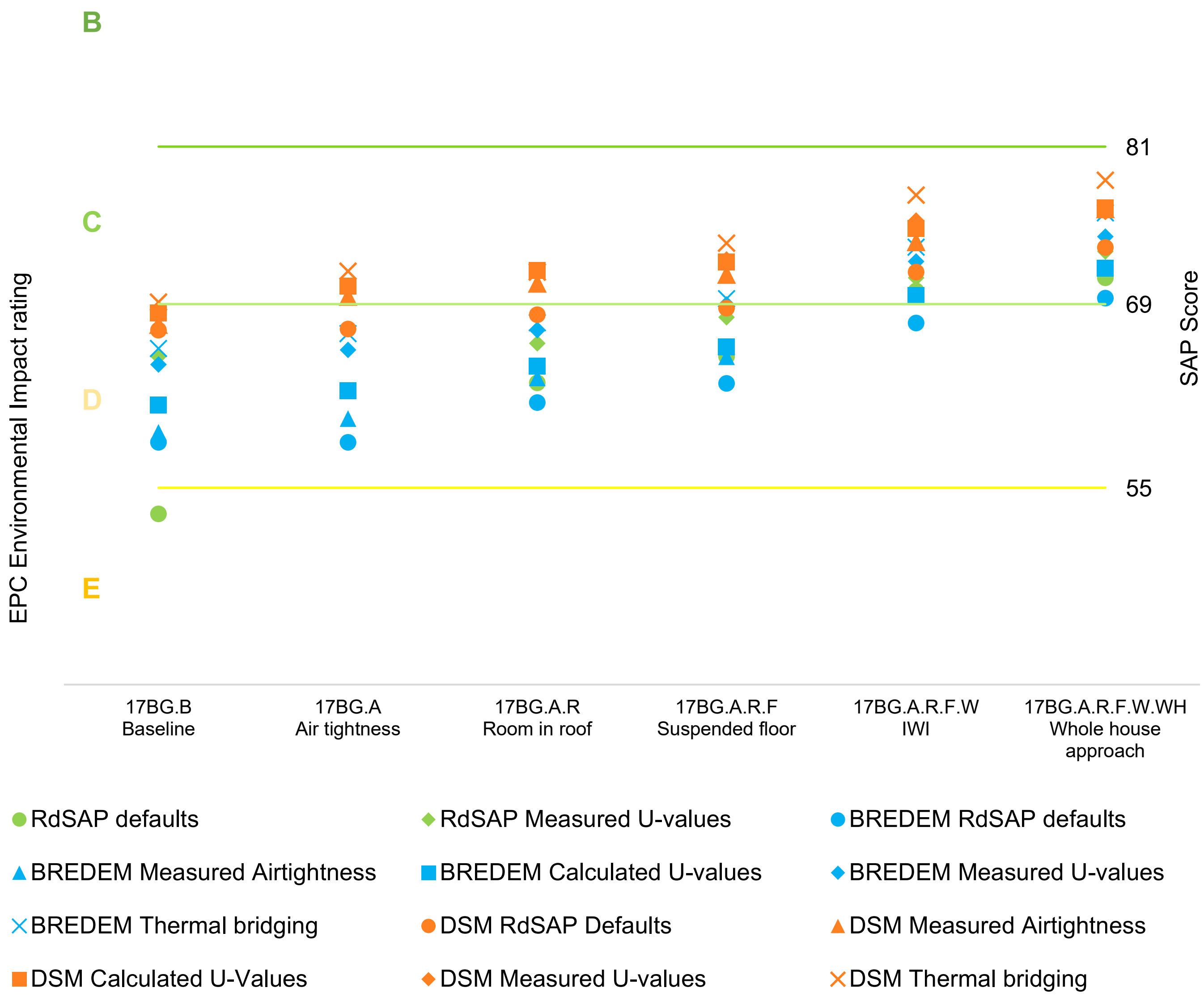

Figure 3-33 Predicted impact of retrofits on EPC band

3.6.2 Impact of retrofits on annual space heating

The Social Housing Decarbonisation Fund (SHDF) Wave 1 evaluates retrofit success by setting a target reduction of 90 kWh per m² for annual space heating for retrofits [14]. The predicted annual space heating demand for this case study's retrofits is shown in Figure 3-34.

- Space heating demand is predicted to be reduced by between 30 % and 55 % depending on which model and assumptions are used.
- Airtightness measures are predicted to reduce space heating demand by between four and 16 % depending on which model is used, though no savings are predicted by RdSAP defaults.
- DSM predicts lower space heating demand than RdSAP and BREDEM, regardless of which inputs are used, due to the way internal gains are calculated.
- RdSAP defaults substantially overestimate heat loss from rooms-in-roof and insulating these has a correspondingly large impact on space heating demand.
- The SHDF 90 kWh per m² target is met in all models except when RdSAP defaults are used in BREDEM.

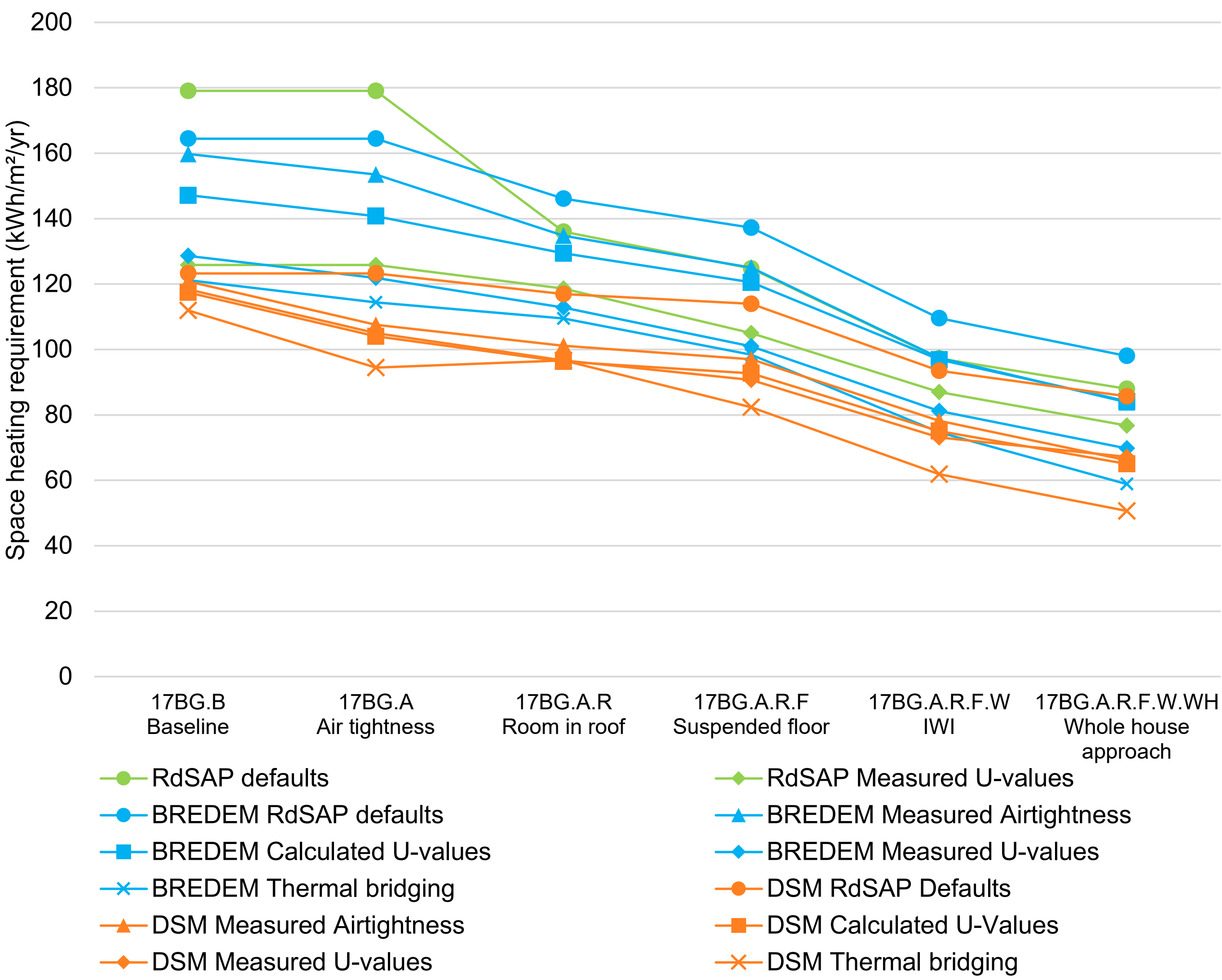

Figure 3-34 Predicted cumulative reduction in annual space heating demand

3.6.3 Impact of retrofits on CO_2 emissions

Heating homes is responsible for around 15 % of the UK's CO_2 emissions [15]. The predicted reduction in CO_2 emissions achieved by the case study home retrofits is shown in Figure 3-35.

- Using RdSAP defaults results in much larger predicted CO_2 savings since it underestimates the baseline energy efficiency of this house.
- RdSAP defaults predicts room-in-roof retrofits to achieve the most CO_2 savings due to assumptions made about geometry and U-values.
- IWI insulation is otherwise the most effective at reducing CO_2 emissions according to most models and calibration stages.
- RdSAP does not predict any savings from airtightness improvements as it is not an input that can be altered.
- DSM generally predicts much lower savings than steady-state models. More research is needed to explore this, though possible reasons are discussed in the following sections.

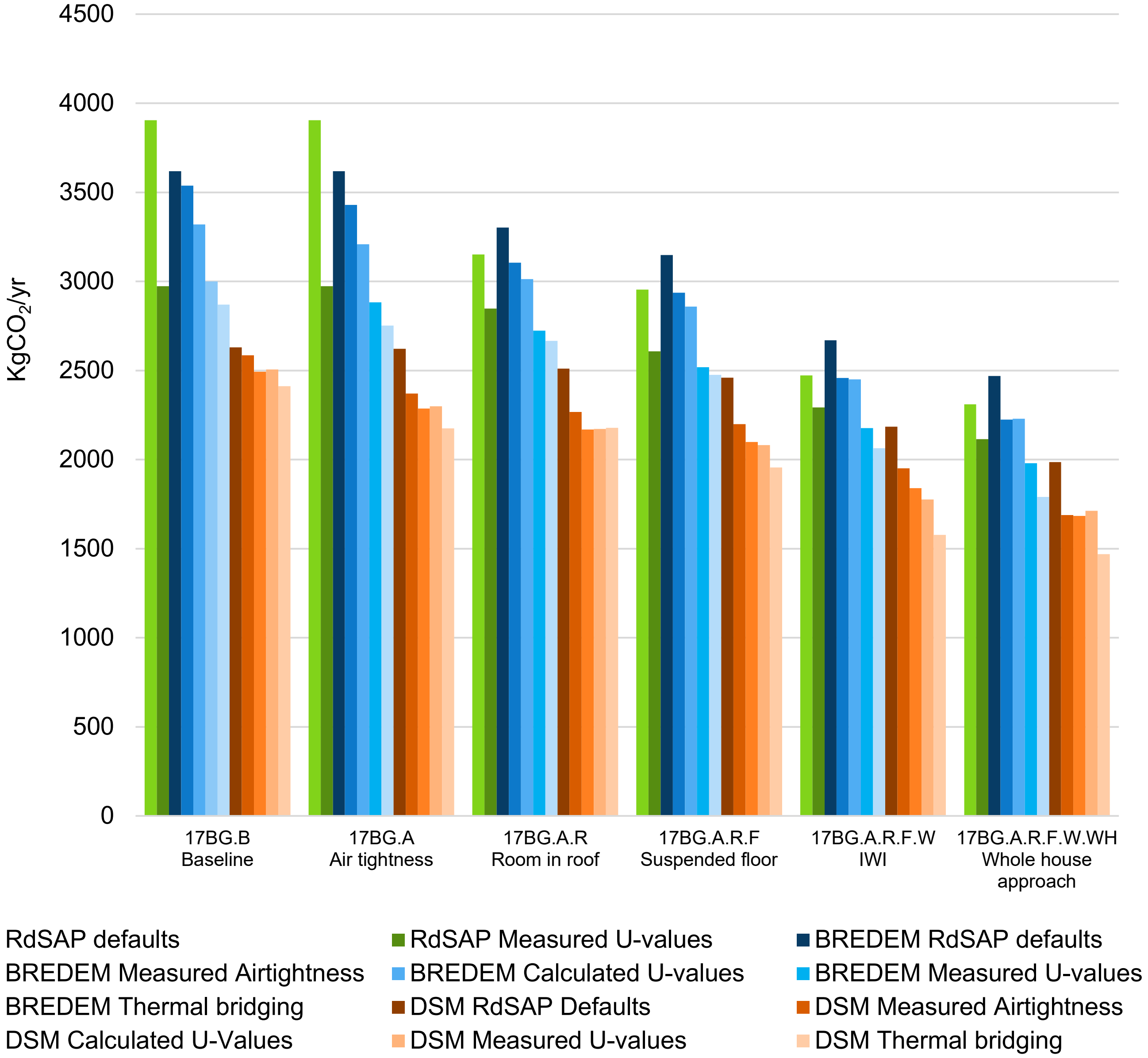

Figure 3-35 Annual CO_2 emission after each individual retrofit

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 include:

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 17BG
For the 17BG baseline scenario, using measured infiltration rate and U-values, BREDEM predicts a space heating demand that is 1,952 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 7,069 kWh, compared with the DSM estimate of 5,888 kWh, a difference of 1,182 kWh. The BREDEM calculations can be further normalised by using the DSM volume of conditioned space (6.53 m^3 less in the DSM model). Following this final adjustment, the BREDEM estimate is 924 kWh higher than the DSM output. Approximately 492 kWh/year of this can be attributed to additional solar gains included in the DSM calculations. This suggests that the other differences between the two modelling approaches have a limited impact of space heating demand predictions.

The influence of solar irradiance on the heat loss through opaque elements in DSM is more complex. However, since 17BG is a back-to-back terrace dwelling, the effect may be less pronounced than in other dwelling forms; this is explored in other DEEP case study reports. The relatively small remainder of the difference (432 kWh) is due to a combination of the other factors mentioned above.

Predicting EPC band, space heating, and carbon reductions summary

This section suggests that models overpredict space heating demand when default data is used, if assessors cannot account for thin levels of insulation.

It also identifies that RdSAP may overpredict space heating demand compared to calibrated versions of both BREDEM and DSM, especially if defaults for room-in-roof heat loss are assumed. The implication of this is that an over estimation of energy and carbon savings may be made, but also that RdSAP underpredicts the initial EPC bands achieved.

In this instance, the EPC band C often required for policy evaluation (e.g. MEES) was not achieved by the whole house retrofit when modelled in RdSAP using age band-related default assumptions. It was, however, achieved when models used more detailed input data. The report also identifies a problem when policy uses other metrics such as space heating demand (e.g. SHDF).

Depending on which model is used will determine if the policy objective has been achieved. It is not yet clear if this underprediction trend is apparent for other house types.

3.7 Overheating risk of retrofitting

The overheating analysis in this section is complementary to this work and uses the overheating assessment method from CIBSE TM59, which is cited in the PAS2035 guidance [17]. A description of this approach is provided in the methodology report. The built form of 17BG means that there is no crossflow ventilation across any façades. Window restrictors, which constrain the opening angles of the window, also mean that the percentage of openable area for each window is particularly small. The openable windows and percentage opening area are shown in Figure 3-36.

Figure 3-36 Percentage of opening area for openable windows

Two metrics are used to assess whether the dwelling will overheat using the TM59 methodology. The first metric is adopted 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 10 pm to 7 am for bedrooms is 32 hours).

Overheating assessment has been carried out at each stage of 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. Results for Criteria A are shown in Figure 3-37.

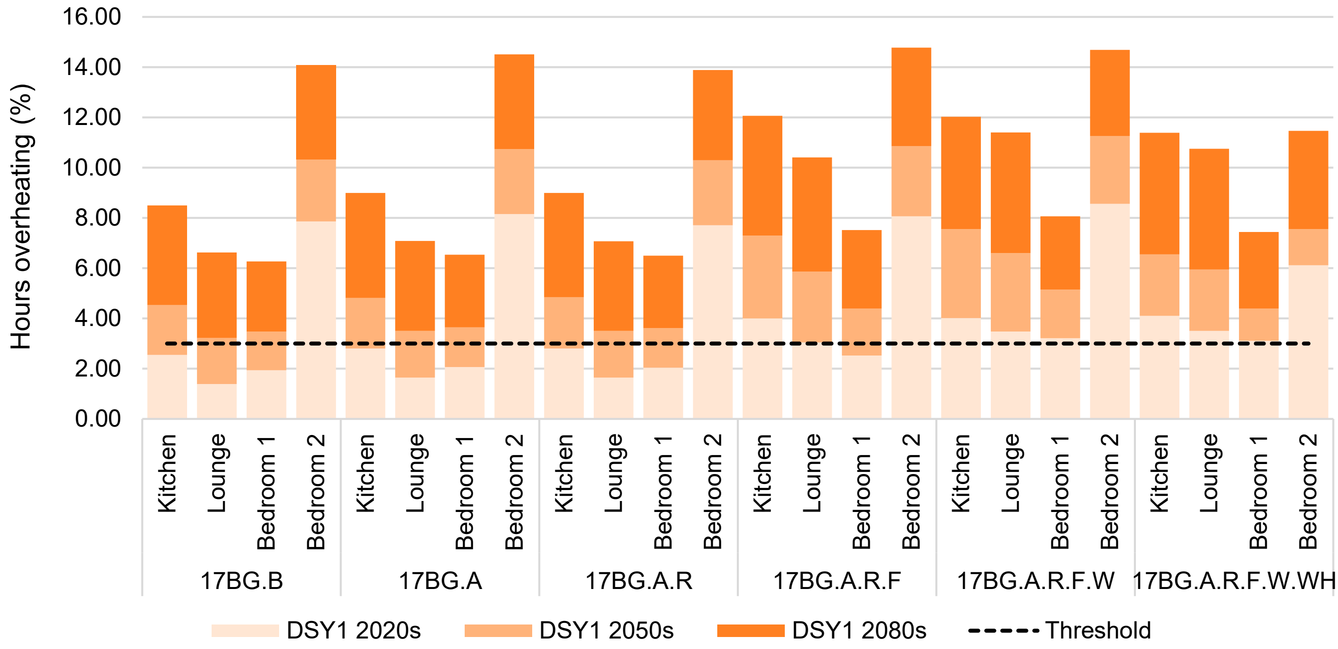

Figure 3-37 Modelled overheating under TM59 Criteria A

In the 2020 weather scenario, it is the room-in-roof bedroom 2 that overheats, meaning that 17BG would fail the TM59 assessment. The dwelling is naturally ventilated, with extract ventilators in the bathroom and kitchen. However, its back-to-back terrace design effectively eliminates any crossflow. Most naturally ventilated dwellings rely on the crossflow of air through the building to ensure sufficient cooling during the hottest periods. It is also evident that the extent of overheating increases at each retrofit stage, as the heat loss from the fabric is gradually reduced.

Although marginal, overheating does reduce slightly at the whole house stage in the bedrooms. This is more distinct in the room-in-roof bedroom (bedroom 2) and is due to the reduced conductive heat gains through the sloping roof (which had additional insulation retrofitted during the final stage).

Prior to the ground floor retrofit, bedroom 2 experienced the highest proportion of overheating, but overheating in the kitchen also increased following the floor retrofit. It is important to note that the kitchen areas include the highest amount of heat gain with the TM59 assessment method.

The bedroom spaces in TM59 are also subject to assessment under Criteria B. Results are illustrated in Figure 3-38.

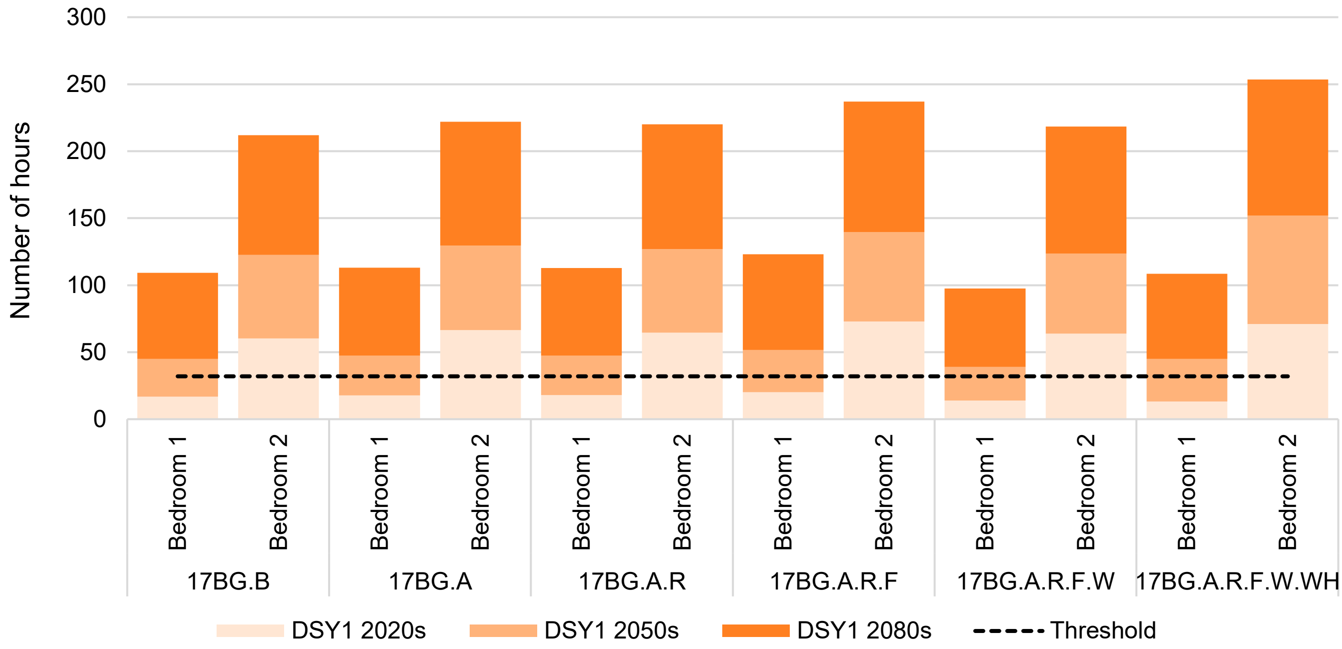

Figure 3-38 Modelled overheating under TM59 Criteria B

The extent of modelled overheating is greater for the bedrooms of 17BG when assessed under Criteria B. However, it is not until the 2050s scenario that bedroom 1 excessively overheats. Bedroom 2 significantly exceeds the number of hours during which it was considered that sleep would be disturbed in all scenarios. This is again related to the lack of any crossflow ventilation, which is exacerbated by the relatively small opening area of the windows. Opening restrictors installed on the windows by the landlord meant that the opening aperture was even smaller than it could be.

Overheating risk of retrofit summary

Whilst overheating in this case study dwelling did gradually increase after each stage of retrofit, up until the whole house stage, the lack of any crossflow ventilation meant that the dwelling was subject to excessive overheating before any retrofit measures were applied.

Conclusions drawn were therefore most pertinent to the dwelling archetype rather than the retrofit activities. Insulating the ground floor increased the extent of overheating in the kitchen in particular; this is in keeping with findings from other ground floor retrofits in the DEEP project.

Increasing the level of insulation in the room-in-roof sloped ceiling did help to reduce overheating slightly during daytime occupation (Criteria A) but did not reduce night-time overheating at all (Criteria B).

As the dwelling failed the TM59 assessment in the 2020 weather scenario, it inevitably overheated more in the future weather scenarios, so this analysis only emphasised the need to consider mitigation in the short-term, rather than indicating future requirements.

3.8 Retrofit costs and payback

This section looks at the costs of undertaking the retrofit described in this case study. 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 and 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.

In this project, the costs of undertaking each retrofit were evaluated to be either: i) enabling works that were linked specifically to getting the house ready for the retrofit (making repairs etc), or ii) the actual cost of the retrofit. 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. Costs associated with decorating were outside the scope of this project but represent around 14% of the cost of IWI [7]. These may be different for EWI, loft and floor insulation, and new windows and doors.

The costs of the 17BG retrofits are outlined in Table 3-10. This includes activities not directly associated with the retrofit itself. Table 3-11 suggests that the costs of the 17BG whole house approach may be slightly higher than may be expected, as undertaking all the retrofits in a single retrofit would be expected to have lower total 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 may be achieved if part of larger project.

The total whole house retrofit cost was £22,200, though it is important to note the doors and windows were not replaced as they had recently been upgraded.

Table 3-11 suggests that around 80 % of the total cost of the retrofit was directly spent on the retrofit, while around 20% was needed for enabling works. The boiler, sanitary ware and kitchen units being removed and replaced was a significant part of this, though replacing floors and needing additional skips also added to the costs. It also explores how the cost of the retrofits relates to the savings that were achieved. Overall, the whole house retrofit cost around £200 to £260 per W/K HTC reduction. The most cost-effective measure was to reduce air leakage, and it also yielded the largest absolute savings.

Table 3-10 Cost of retrofits

Retrofit	i) Retrofit activity	Retrofit costs	ii) Additional enabling work required	Enabling work costs
17BG.A Airtightness	Seal penetrations Cover unneeded air bricks Box in services Draught strip windows	£ 2,100	Repointing and replastering around vents	£ 350
17BG.A.R Room-in-roof	Replace knee & dormer walls Insulate knee & dormer walls Insulate gable walls including intermediate floor void Replace skirting	£ 3,000	Remove radiator Extend wall sockets and light switch	£ 400
17BG.A.R.F Suspended ground floor	Lift and replace floorboards Insulate between joists Replace skirting	£ 1,700	New floor needed Extra skip	£ 900
17BG.A.R.F.W Internal wall insulation	Remove wall drylining Install insulation including intermediate floor void Replaster walls Replace skirting	£ 3,600	New floorboards Remove sanitary ware Box in services Extra skip	£ 800
17BG.A.R.F.W.WH Whole house approach	Remove, insulate & replace sloping ceiling, & dormer roof Insulate loft Remove wall drylining Install insulation including intermediate floor void Replaster walls Replace skirting	£ 7,900	Remove & refit boiler New skirting boards Remove & refit kitchen units	£ 1,800

The whole house approach (17BG.WH) was also among the least cost-effective interventions. This was in part because there was already some thin IWI on the walls, meaning the upgrade to thicker IWI was less impactful. However, it was also expensive to undertake these final improvements, because of the need to move items away from the wall to insulate behind them (boiler and kitchen units). This final stage alone made up 44 % of the entire retrofit costs. This high-cost activity for marginal energy reward is an obstacle to IWI and may be a disincentive for compliance with PAS2030 standards.

Table 3-11 considers how the costs of the retrofits are split between labour and materials, which may be useful when considering how to reduce the total costs of retrofits in the future and where innovations are needed. It appears that the major cost of retrofits is labour. Depending on which measure is installed, this may be just over half to three quarters of the total cost. Time saving innovations in the retrofit industry may therefore be desirable.

Table 3-11 Breakdown of cost of retrofits

Retrofit	Labour	Materials	Total cost	Proportion total cost	Treated area (m²)	Cost per area (£/m²)	Benchmark (£/m²) [19]
17BG.A	76%	24%	£ 2,450	11%	122[9]	£ 20	-
17BG.A.R	53%	47%	£ 3,400	15%	21	£ 160	-
17BG.A.R.F	67%	33%	£ 2,250	10%	23	£ 97	£38 - £92
17BG.A.R.F.W	61%	39%	£ 4,400	20%	41	£ 108	£113 - £148
17BG.A.R.F.W.WH	57%	43%	£ 9,700	44%	26	£ 375	-
Total	**60%**	**40%**	**£ 22,200**		122	£ 181	**-**

It is useful to consider the HTC savings (W/K) achieved per £ spent. This may provide useful insights for predicting how cost-effective different retrofits are to inform future national retrofit schemes. These are shown in Figure 3-39. However, the data is from a single case study and may not be representative for different house types, other retrofit products, or geographic locations. The costs vary tremendously, plus no savings were measured for the floor retrofit, so this is excluded. The high costs for the whole house approach were due to the boiler removal and replacement of the room-in-roof ceilings (both high-cost activities), plus, there was already some thin insulation in place, and only a relatively small wall area was insulated. The airtightness measures were around four to five times more cost effective than the fabric measures, though there are uncertainties over the measured HTC reductions achieved by these.

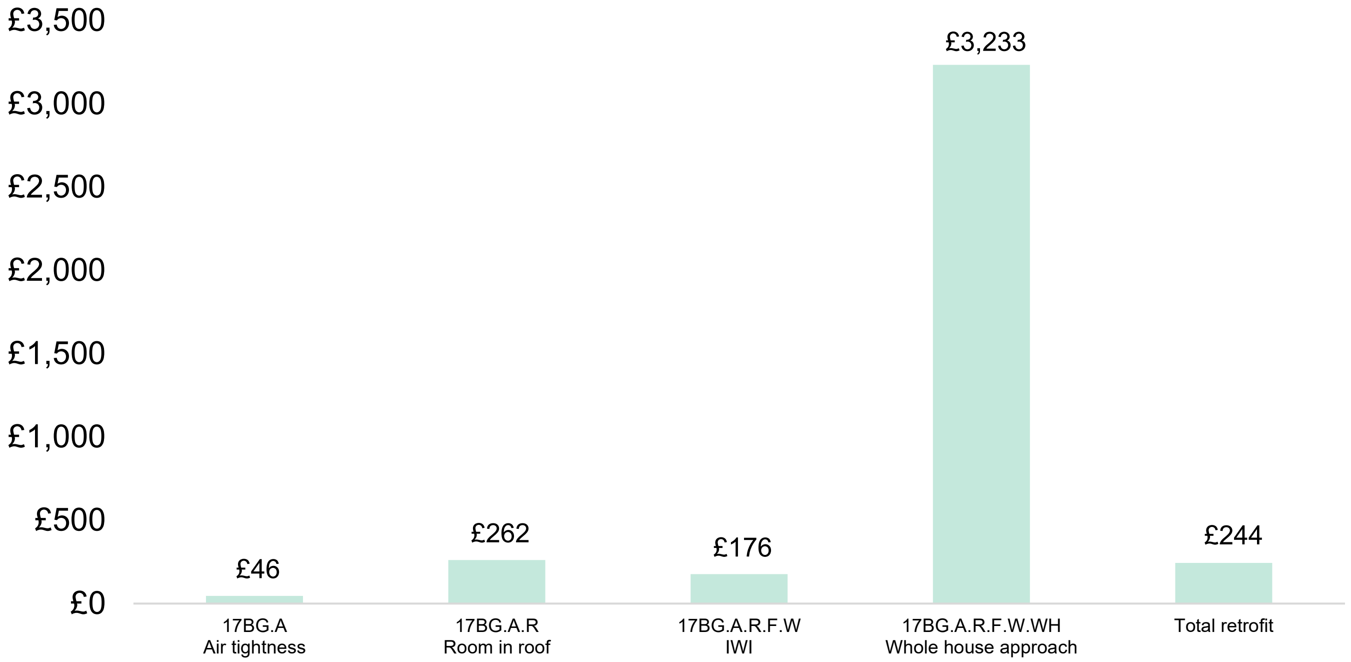

Figure 3-39 Cost per W/K reduction in HTC

[9] Assuming whole house heat loss area

3.8.1 Predicted fuel bill savings

The impact of the retrofits on household dual fuel bills is shown Figure 3-40 using the SAP fuel prices of 3p per kWh gas and 13p per kWh electricity. These are values do not reflect current fuel prices and are shown only as an illustration.

The predicted reduction in annual dual fuel bill for the house, achieved by the retrofits, varies depending on which model is used, as shown in Figure 3-40.

- Reducing space heating demand by between 30 % to 55 % achieved fuel bill reductions equivalent to 19 % to 34 %, depending on which models and assumptions are used.
- DSM predicts fewer savings are possible overall, since its baseline house has lower bills.
- Room-in-roof retrofits achieve substantially higher fuel bill savings in RdSAP when defaults are used (16 %) due to simplifications made in the software; other models only predict reductions up to 7 %).
- IWI is responsible for a large proportion of the overall fuel bill savings of 8 % to 12% off the baseline.

Changes to fuel prices will directly impact the predicted savings shown here and have implications for the payback periods discussed in the following section.

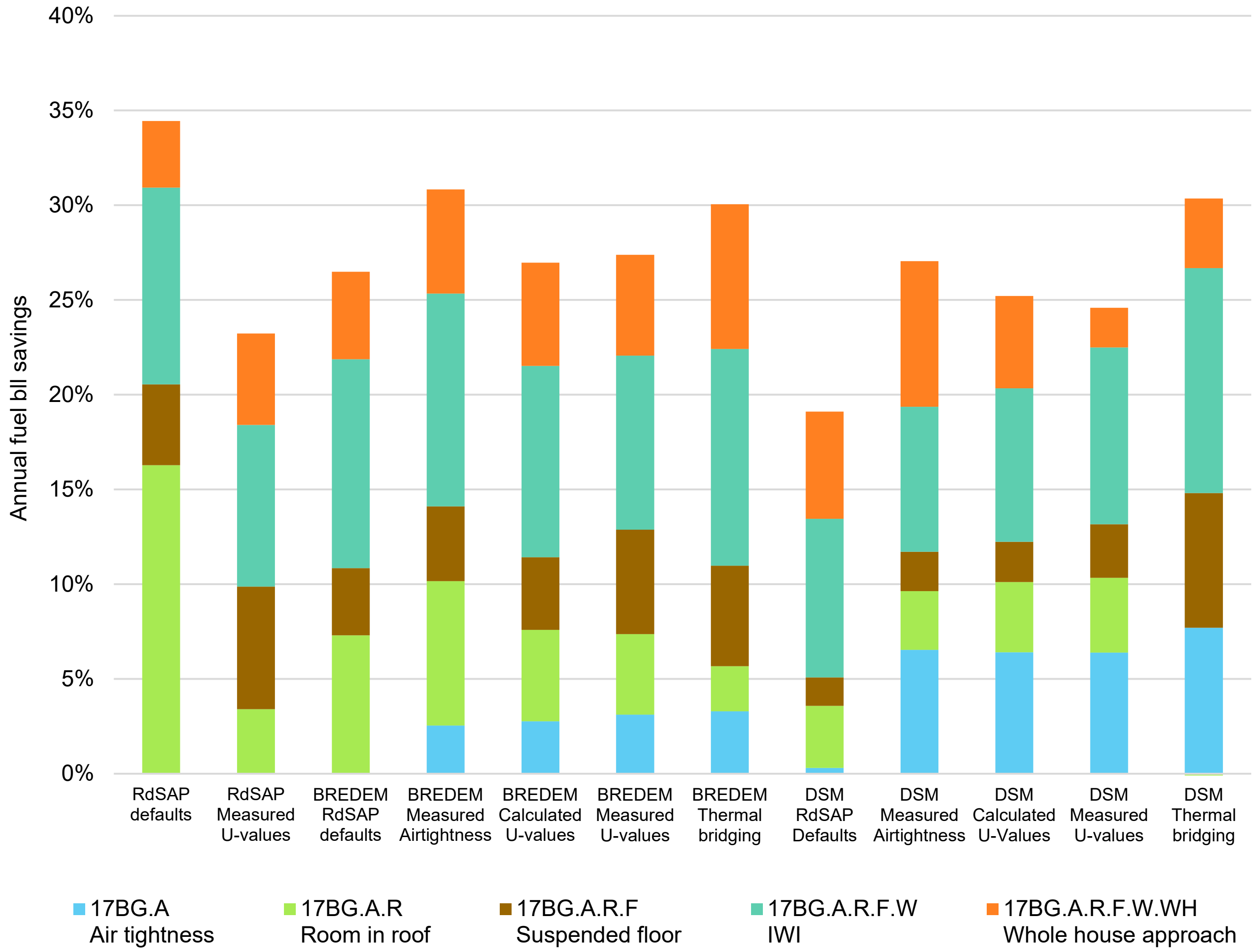

Figure 3-40 Predicted annual fuel bill savings achieved by the retrofits

3.8.2 Predicting simple payback of retrofits

The simple 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 3-41. Recent fuel and retrofit price increases will significantly affect payback rates.

- Payback rates vary enormously depending on which model and input data are used.
- The most financially viable retrofit appears to be the room-in-roof insulation, though this is likely to be an optimistic prediction due to the way RdSAP defaults overpredict heat loss from uninsulated rooms-in-roof.
- DSM has longer payback years generally than RdSAP and BREDEM since it predicts lower space eating demand.
- All retrofits have payback rates above 15 years; the guidance in Paragraph 5.9 of Approved Document Part L1B states retrofits with payback above this are not considered financially viable and therefore limiting U-values need not be achieved.
- Whole house approach improvements have the longest paybacks since they are so expensive to undertake, e.g., removing wall mounted boilers and kitchen units.

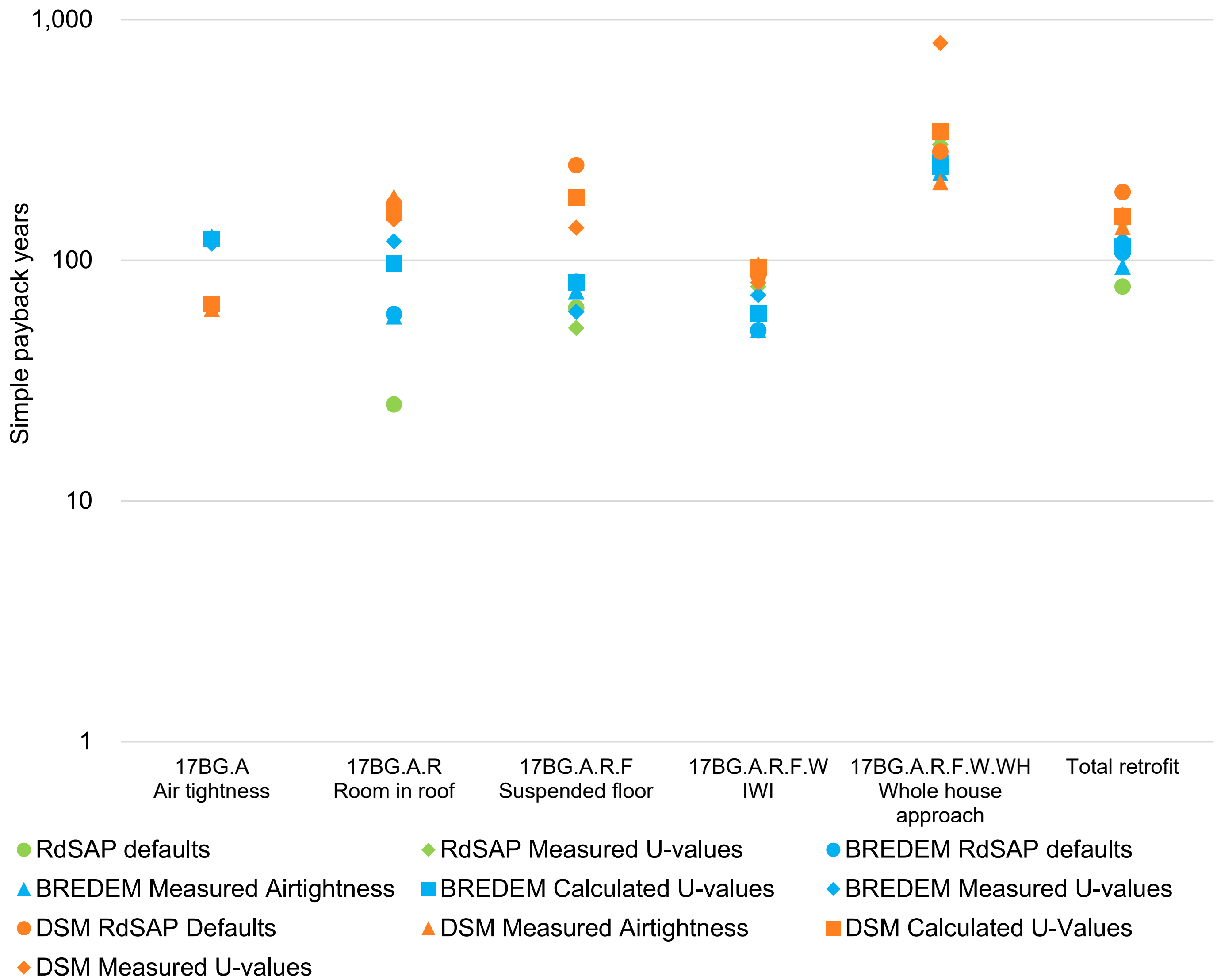

Figure 3-41 Simple retrofit paybacks

Retrofit costs summary

The retrofit costs for 17BG were slightly higher than may have been expected. Since this is a research project, it is not known if economies of scale may have been achieved if all the retrofits were installed at the same time, or as part of a multi-home retrofit project.

The whole house approach made up 44 % of the total costs and yielded only marginal fuel bill savings, while airtightness measures were around four to five times more cost effective than the fabric measures.

When RdSAP defaults are used, EPCs overestimate heat losses in uninsulated homes, and so predict much larger savings from retrofits and shorter payback rates than may be experienced.

The retrofits generally had very long simple payback periods, much more than the 15 years identified in the Building Regulations for England and Wales. However, future price rise estimates, and discount rates may alter these estimates.

Reductions in fuel bills in the order of £115 to £286 per annum are predicted following the whole house retrofit, depending on which software and input data are used. This is a relatively small house with large areas of party walls, and so more research is needed to understand if these trends are observed in other house types with similar or different retrofits.

3.9 Retrofit moisture risks

To measure the risk of surface condensation before and after the retrofits, surface temperature measurements were undertaken in six locations throughout 17BG, at sites where thermal bridges and discontinuities of insulation were expected to pose a risk. Surface temperature sensors were only installed for the final three stages of the retrofit (17BG.F, 17BG.W and 17BG.WH), since the walls were the final elements to be insulated. Thus, the floor insulation stage 17BG.F acts as the base case for these measurements.

T-type thermocouple temperature sensors were placed on the building fabric and monitored during the coheating periods from the IWI phase onwards (See the DEEP 2.01 Report, section 2.7 for methods). The quasi-steady-state conditions of the coheating test provide comparably steady conditions for comparison with numerical thermal simulation. The sensors were removed to allow retrofit 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.

The risk of condensation occurring does not mean condensation will necessarily manifest. Risk may be mitigated against by ensuring adequate ventilation in the dwelling, 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.

Temperature factors are usually used in conjunction with steady-state simulations. In this study, to validate the stability of temperature factors calculated using in-situ surface temperatures, the averaging method in BS ISO 9869: 2014 was adopted. Where a surface temperature location was unable to satisfy the validation steps, it is considered to have failed. Further details of the methods used can be found in DEEP Report 2.01: DEEP case study methods.

3.9.1 Kitchen measured condensation risks

Figure 3-42 shows the location of the surface temperature measurements undertaken in the kitchen. These locations were chosen since they help describe how a room-by-room approach to IWI can increase condensation risks. The kitchen and bathroom were left in their original condition during the IWI retrofit phase (17BG.W), and only insulated afterwards during the whole house approach retrofit (17BG.WH). Thus, the difference in risk will provide some insights into the likely condensation risks of a room-by-room retrofit approach.

Figure 3-42 Kitchen thermocouple sensor locations: Left 17BG.W; Right 17BG.WH

Table 3-12 shows the temperature factors for the kitchen sensors and as can be seen, it indicates that the wall above the cabinets was not at risk of condensation in any phase. However, before the wall insulation was added (phase 17BG.F) all the sensor locations below the kitchen counter were found to have values of f_{Rsi} below the 0.75 threshold and can be considered to have been at risk of condensation and mould growth.

Table 3-12 Temperature factors in kitchen during each retrofit stage

Kitchen, values for f_{Rsi}						
Phase	1-Under sink	2-Under counter, low	3-Under counter, high	4-Adj. window	5-Window jamb	6-Partition junction
17BG.F	0.51 (±0.08)	0.57 (±0.14)	0.72 (±0.10)	0.86 (±0.05)	N/A	N/A
17BG.W	0.71 (±0.05)	0.75 (±0.06)	0.76 (±0.05)	0.83 (±0.06)	N/A	N/A
17BG.WH	N/A	N/A	0.86 (±0.02)	0.92 (±0.02)	0.88 (±0.05)	0.84 (±0.04)

Although there was no alteration to the kitchen wall fabric insulation between 17BG.F and 17BG.W, the risk of condensation below the counter fell when the rest of the house had IWI fitted. However, this is likely to be because the kitchen units were removed by the installer to investigate the future retrofit stages and only placed back in-situ, not sealed and secured in place. This meant that the wall surface under the cabinets was better ventilated than may be the case when the kitchen is refitted. This highlights the importance of not only maintaining reasonably warm internal temperatures to mitigate condensation risk, but also ensuring adequate circulation of air.

Having no condensation risk on the kitchen wall above the kitchen worktops after the adjacent room had IWI insulated, means that there may not have been any new risks introduced because of the room-by-room approach to IWI. This is counter to previous findings [20]. However, when the kitchen wall was finally insulated in the 17BG.WH phase, investigations showed that thin IWI (TIWI) was present on the walls already. This may have been responsible for reducing the risk. More data on a room-by-room approach to IWI is therefore needed where TIWI is not already installed. In the final phase (17BG.WH), the installation of IWI in the kitchen eliminated all risk of condensation across the wall. The insulation phase improved all values of f_{Rsi}, and the window jamb and partition wall junction were not found to be condensation risks.

3.9.2 Living room measured condensation risks

Table 3-13 shows the temperature factors for the living room sensors shown in Figure 3-43. These were focused on the external corner wall, since this is an area where thermal bridging can occur in uninsulated dwellings; and the reduction in risk made by the insulation was recorded.

Figure 3-43 Living room thermocouple locations (17BG.W)

Table 3-13 confirms that the uninsulated gable wall is at risk of surface condensation before the introduction of insulation, but all risk is removed from all the walls once IWI is installed.

The front wall and front wall - gable wall junction were found to not be at risk before the IWI retrofit However, as mentioned before, this is likely due to TIWI already being installed in the base case condition.

Table 3-13 Temperature factors in living room during each retrofit stage

Living room, values for f_{Rsi}				
Phase	1- Front wall	2-Front - gable wall junction	3-Gable wall	4-Beneath skirting
17BG.F	0.82 (±0.04)	0.86 (±0.03)	0.52 (±0.09)	0.71 (±0.06)
17BG.W	0.88 (±0.04)	0.77 (±0.05)	0.89 (±0.04)	Fail
17BG.WH	0.89 (±0.05)	0.78 (±0.08)	0.90 (±0.04)	0.34 (±0.05)

The space below the skirting board appears to experience a significant reduction of f_{Rsi} following the 17BG.W retrofit. However, since no change to the wall or floor were experienced between 17BG.W and 17BG.WH, it is likely that this change may be due to a problem with the sensor placement or some unknown change in air movements.

3.9.3 Bathroom measured condensation risks

Five sensors were installed in the bathroom, though it was not possible to capture data for all the locations at each retrofit stage. The wall behind the boiler in the bathroom, like in the kitchen, was deliberately omitted from the IWI retrofit, to investigate the room-by-room approach. Again, it was observed afterwards that TIWI had already been installed and so it was not possible to compare a completely uninsulated wall with an insulated wall. The sensor locations are shown in Figure 3-44, and the temperature factors are listed in Table 3-14.

Figure 3-44 Bathroom thermocouple locations (17BG.W)

TIWI was already installed to the plane surface of the wall in the bathroom, to the left of the boiler. However, it was omitted on the small areas of wall above, below, and to the right of the boiler, which was fixed direct to the plaster. A colder section of wall can be observed above and to the right of the boiler in Figure 3-45 to illustrate this. Thus, the wall to the left of the boiler was not at risk of condensation before the TIWI was replaced by full IWI (17BG.W). The temperature factor further improves when IWI was later installed above, below, to the right, and behind the boiler installation (17BG.WH).

Figure 3-45 Existing TIWI installed to the left of the boiler (warmer), uninsulated wall above and to the right of the boiler (colder)

Conversely, the wall beneath the boiler’s pipework, which was boxed in, does appear to present a condensation risk prior to insulation (sensor 3). This risk was present as there was no TIWI installed behind the boxed-in area or to the right of the boiler, as shown in Figure 3-46, where the pipes are visible after the boiler had been removed. This highlights that if there are discontinuities in IWI or TIWI around services then there may be a risk of surface condensation, though this may make the retrofit more disruptive and costly. Unfortunately, the averaging method was unable to validate 17BG.W and 17BG.WH f_{Rsi} at this location, so was deemed to ‘fail’ in Table 3-14 and it cannot be confirmed if the interventions changed the level of risk.

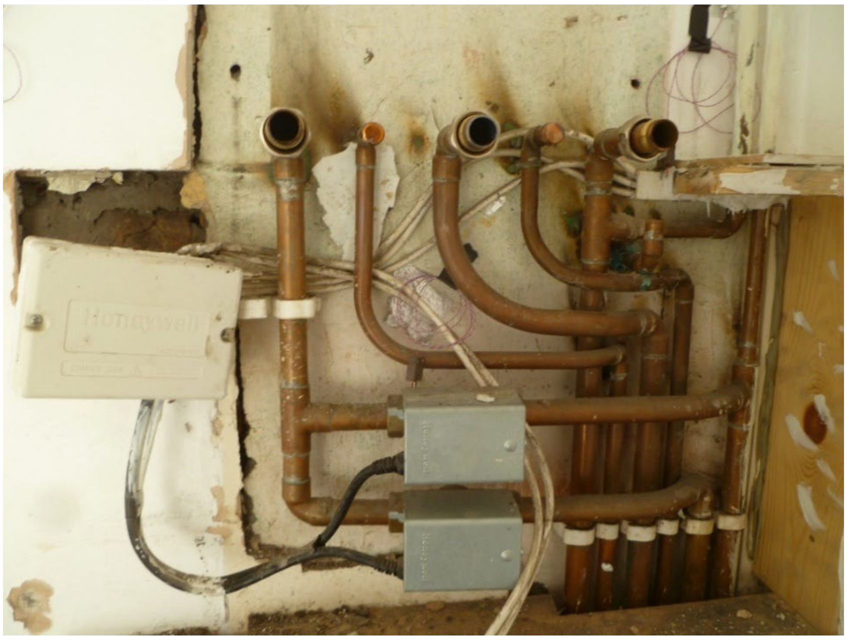

Figure 3-46 TIWI not continued behind boxed in services

There is also some indication from these measurements that the room-by-room approach to IWI could introduce risk. Sensor 4, located to the right of the boiler, by the partition wall, shows that there was initially no risk when there was only TIWI installed to the adjacent side of the partition wall (17BG.F). However, after the adjacent room had full IWI fitted in the 17BG.W stage, the temperature factor here dropped to 0.68, suggesting that a new risk was created.

Thus, if the room-by-room approach is adopted, this data suggests there is a chance risks will be introduced for uninsulated rooms, particularly close to junctions between uninsulated walls and insulated walls. In this case it is possible that the section around the partition wall, which had insulation on one side of the partition but not on the other, shifted the surface temperature profile around the thermal bridge.

Table 3-14 Temperature factors in bathroom during each retrofit stage

Bathroom, values for f_{Rsi}					
Phase	1-Adj. window	2-Below sink	3-Boxing under boiler	4-Pipe run	5-Window jamb
17BG.F	0.87 (±0.10)	0.93 (±0.07)	0.66 (±0.10)	0.83 (±0.05)	N/A
17BG.W	0.88 (±0.02)	N/A	Fail	0.68 (±0.03)	0.68 (±0.05)
17BG.WH	0.91 (±0.03)	N/A	Fail	Fail	0.93 (±0.02)

The window jamb in the bathroom was also determined to have a risk of condensation (f_{Rsi} of 0.68) before being insulated (17BG.F). This is likely to be because the TIWI that was already installed had not included insulation on the window reveals. Following the IWI installed in the 17BG.WH phase, which did insulate the window reveals, this risk was eliminated, and the temperature factor improved to 0.93. This highlights the importance of including window reveals in any IWI design.

3.9.4 Bedroom measured condensation risks

The sensors in the bedroom were installed on the adjacent partition wall junction to the bathroom and to the window and intermediate floors, as shown in Figure 3-47.

Figure 3-47 Bedroom thermocouple locations (17BG.W)

As can be seen in Table 3-15, the bedroom floor void appears to be at risk of condensation in all cases, though it does improve once the wall is insulated (17BG.W). It further improves after insulation is added to walls in adjacent rooms and in the room-in-roof. However, it is not clear why this would be the case and may be associated with an error in the sensor placement or some unknown change in air movements.

Table 3-15 Temperature factors in bedroom during each retrofit stage

Bedroom, values for f_{Rsi}					
Phase	1-Floor void	2-Partition junction	3-Centre wall	4-Window jamb	5-Above skirting board
17BG.F	0.45 (±0.09)	0.88 (±0.03)	0.83 (±0.09)	0.60 (±0.06)	N/A
17BG.W	0.66 (±0.10)	N/A	0.90 (±0.02)	0.66 (±0.03)	0.86 (±0.04)
17BG.WH	0.74 (±0.09)	N/A	0.92 (±0.04)	0.68 (±0.13)	0.89 (±0.05)

The external wall-to-partition junction in the bedroom was not at risk of condensation in the base case model, and since no risk was present, the sensors were relocated above the skirting board for the final retrofit stages. Neither the plane wall at the centre, nor above the skirting board, were determined to be at risk of condensation. This confirms that both TIWI and IWI can reduce condensation risk in plane elements.

The window jamb was monitored at the junction with the window frame; this location was at risk of condensation during all phases. This was anticipated for the base case (17BG.F) since there was no insulation on the window reveals. This was not expected to remain when the IWI was installed (17BG.W). Although the values of f_{Rsi} increased, they did not rise above the 0.75 condensation risk threshold. This may be due to air leakage around the window. However, the finding suggests that insulating window reveals may not always eliminate condensation risk.

3.9.5 Room-in-roof measured condensation risks

The party walls were identified as an area of possible risk in the room-in-roof and so measurements were taken here, as shown in Figure 3-48, and the results from these are in Table 3-16.

Figure 3-48 Room-in-roof thermocouple locations (17BG.W)

In 17BG.F, the base case for the surface temperature measurements, the external gable wall in the room-in-roof had already had insulation installed as part of a previous retrofit. This meant that neither the plane gable wall nor the party wall were found to be at risk of condensation during any phases of the retrofit.

Table 3-16 Temperature factors in room-in-roof during each retrofit stage

Room-in-roof				
Phase	1-Gable, floor void	2-Gable wall	3-Gable - party wall junction	4-Party wall
17BG.F	0.90 (±0.05)	0.89 (±0.03)	0.74 (±0.07)	0.94 (±0.05)
17BG.W	0.91 (±0.03)	0.95 (±0.10)	0.78 (±0.08)	0.95 (±0.07)
17BG.WH	0.91 (±0.03)	0.91 (±0.05)	0.79 (±0.07)	0.95 (±0.03)

Conversely, the surface temperature at the party to gable wall junction was found to have a f_{Rsi} of 0.74, below the 0.75 threshold and so representing a risk. However, in subsequent phases the value of f_{Rsi} at the junction was just above 0.75, despite no changes taking place to these elements. It is possible this change is due to the consistency of the conditions during each phase, the accuracy of the sensors, and changes in their placement.

Retrofit risks summary

Installing TIWI or IWI will reduce surface condensation risk. However, risks may still occur if a whole house approach is not adopted, e.g. if there are discontinuities in the insulation, or if only one side of a party or partition wall is insulated.

Room-by-room approaches to IWI may therefore pose an elevated risk for the uninsulated room, although this risk may not always occur if TIWI is used.

Window reveals, intermediate floor voids, and boxed-in areas should always be included in IWI retrofits. If left uninsulated, they can be at risk of condensation.

Installing IWI to these areas can be difficult to achieve in practice, especially if undertaking window replacements, having plumbing work, or a new boiler installed, at a different time to wall insulation.

4 Conclusions

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

Internal wall insulation

This case study confirmed previous work regarding the effectiveness of solid wall insulation, showing that internal wall insulation (IWI) installed on both its external walls reduced the home's heat transfer coefficient (HTC) by (19 ± 9) %. This was also in line with modelled predictions.

It also confirmed previous findings that uninsulated solid walls pose surface condensation risks, and that IWI can remove these risks. It furthermore provides new findings showing that condensation risks at the floor to wall junctions are also eliminated by IWI retrofits, even when the floor remains uninsulated.

Additional investigations identified that existing condensation risk can, however, be worsened. This can occur where there are discontinuities in the IWI, for example, by not insulating behind wall-mounted objects. Additionally, if a room-by-room approach to IWI is adopted, existing condensation risks on the cold side of partition walls can get worse. This concurs with the previously observed phenomenon that when IWI is installed in one home, condensation risk increases in the neighbouring home, on the uninsulated side of the party wall.

Investigations into interstitial condensation risks and moisture accumulation in walls where IWI is installed did not form part of the case study but are important to informing a risk-based approach to IWI. DEEP Report 6.04 uses hygrothermal simulations to explore these risks associated with IWI.

Airtightness improvements

The case study also provided new information on the impact of improving the airtightness of solid walled homes on whole house heat loss. A 40 % reduction in air permeability meant the house achieved airtightness levels comparable with new build homes and resulted in a (27 ± 14) % reduction in HTC. This home had particularly high air leakage, yet the other fabric retrofits did not materially improve airtightness. This suggests that without specifically addressing airtightness during a retrofit, heat loss from uncontrolled air leakage could undermine the fabric improvements.

Caution is needed in interpreting the measured results, however, as the test had a large uncertainty associated with it, due to non-ideal conditions. Furthermore, the measured HTC saving was higher than the total amount of heat loss deemed to be associated with air leakage by closing-the-loop analysis (using the n/20 rule). Additionally, the measured savings were also substantially higher than predicted by the models.

More research is needed to explore heat loss associated with air leakage in homes. This case study suggests that airtightness improvements may have a role in future retrofit policy, though more investigations are needed to explore its impact on space heating, as well as its relationship with ventilation, comfort, damp, and air quality. These were outside the scope of DEEP.

Room-in-roof insulation

The case study also provides insights into the benefits of insulating rooms-in-roof (RIR), for which little data currently exists. A (9 ± 19) % reduction in HTC was measured when the knee walls and gable wall were insulated with IWI, leaving the sloping roof and dormer uninsulated. Uninsulated RIR were calculated to have particularly high risks of surface condensation and this partial approach to the retrofit, leaving elements uninsulated, further increased the risk of condensation in areas where there were discontinuities in the insulation. Returning to insulate the sloping ceiling and dormer removed or lessened these condensation risks and provided a small amount of additional HTC reduction: a further (3 ± 9) %.

These measurements also suffered from high levels of uncertainty, though the models predicted HTC savings between 2 % and 24 %. Further investigations into the way RdSAP allows assessors to simplify RIR highlighted that it is probable that EPCs for homes with RIR are over estimating heat loss. In this case study, this caused an increase in HTC of around 13 %, meaning the uninsulated home was awarded an EPC Band E rather than a D. This overestimate of heat loss also meant the EPC predicted savings for RIR retrofits were more than double that which may be likely to be achieved. The case study has shown that RIRs are prone to condensation risk. While retrofits can remove some risk, if discontinuities persist post retrofit, they can also increase it. RIR retrofits could, however, play an important role in future retrofit policy, though the way in which it is represented in EPCs needs further investigation.

Suspended timber floor insulation

Large improvements in measured floor U-values, achieved by installing mineral wool between the floor joists, did not translate to reductions in measured HTC. This case study home had a relatively small floor and there was an unventilated basement below it, meaning the findings may not be representative of floor retrofits in other house types. It is, therefore, not clear from this case study what the potential for floor insulation may be nationally. Eight case studies in DEEP investigate the impact of floor insulation and the combined findings from these are discussed in the DEEP Methods 2.0 Report.

y-values and thermal bridging heat loss

Retrofitting the house halved the thermal bridging heat loss in the house, which fell from 25.6 W/K to 10.7 W/K. However, mid-retrofit, when there were discontinuities in the RIR, and prior to the IWI insulation, the amount of thermal bridging heat loss increased to 31.7 W/K. The findings raise questions over the way thermal bridging heat loss is accounted for as a static y-value of 0.15 in RdSAP both pre- and post-retrofit. The y-value for this case study home was calculated to be 0.2 pre-, and 0.08 post-retrofit, which indicates that there may be value in revising the default y-values used in RdSAP to account for different house types and levels of retrofit.

Whole house approach to retrofit

The retrofit of this case study was initially a piecemeal retrofit of the previously discussed measures, followed by a final retrofit to join these individual elements together. This included installing IWI behind wall mounted obstacles, installing IWI in all rooms, and insulating the sloping roof and dormer to remove discontinuities in the RIR insulation layer. These activities successfully removed surface condensation risks from every junction. Pre-retrofit, 21 out of 30 junctions posed a risk, and after the piecemeal retrofit 12 junctions still posed a risk.

However, undertaking this final stage of the retrofit was costly, making up 43 % of the total cost. It also resulted in only 3 % additional HTC reduction compared to the piecemeal retrofits. These findings suggest that adopting a whole house approach to retrofit is important for management of surface condensation risk, though it can add substantial costs to projects.

This case study house had mechanical extraction fans in the bathroom and kitchen, and trickle vents on the windows. Long-term monitoring of the home’s internal environment pre- and post-retrofit while occupied was out of scope of the project. Thus, an aspect of the whole house approach to retrofit that could not be investigated in DEEP was the impact of ensuring adequate ventilation in the home and how this combines with the retrofit to impact health, comfort, moisture risk, and indoor air quality.

Predicting heat loss and retrofit savings

This case study suggests that HTCs predicted by EPCs can be substantially higher than HTCs that are measured. The reason for this in the case study home was mainly due to inbuilt assumptions in RdSAP around room-in-roof geometries, which caused the home to be awarded an EPC E rather than a D, a jump of 12 SAP points. When these were overridden, the predictions were more aligned, though still overpredicted heat loss. The post-retrofit home was, however, awarded an EPC band C by most models.

The case study also confirmed that replacing default data inputs with measured and calculated data on airtightness, U-values, and thermal bridging, can reduce the degree of over prediction taking place. This was worth between two and seven SAP points depending on the input data and model used.

There are two main implications of over prediction of heat losses. Firstly, some homes may miss the national EPC band C target, even if they achieve the minimum standard of energy efficiency in practice. Secondly, the retrofit savings predicted for this house by the EPC are double that which can be achieved in practice, making retrofits appear more cost effective than they are.

Overriding the room-in-roof geometry assumptions had a more significant impact than replacing the default inputs with measured data. There is scope for EPCs to be made more accurate by addressing conventions in the modelling procedure, beyond simply providing more representative input data. However, comparisons of measured and modelled heat loss in more house types, with differing levels of measured and default input data, is needed to understand how this relationship varies across house archetypes and ages.

Cost effectiveness

Uncertainty around future fuel and retrofit prices make it difficult to describe the cost effectiveness of retrofits. In this case study the whole house retrofit cost £22,000. Very simple assessments suggest a payback period of between 78 and 192 years, though this will be substantially affected by future fuel price assumptions. The most cost-effective retrofit based on measured HTC improvement was to reduce air leakage. However, because the benefit of this was predicted to be much lower in the models, this did not achieve particularly low payback periods. Instead, the IWI retrofit, which achieved the greatest predicted HTC savings, was deemed to be the most cost effective by the models.

The whole house approach retrofit activities were the least cost effective. More work is needed to investigate and articulate the non-financial benefits of lower risk retrofits that are achieved when adopting a whole house approach.

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